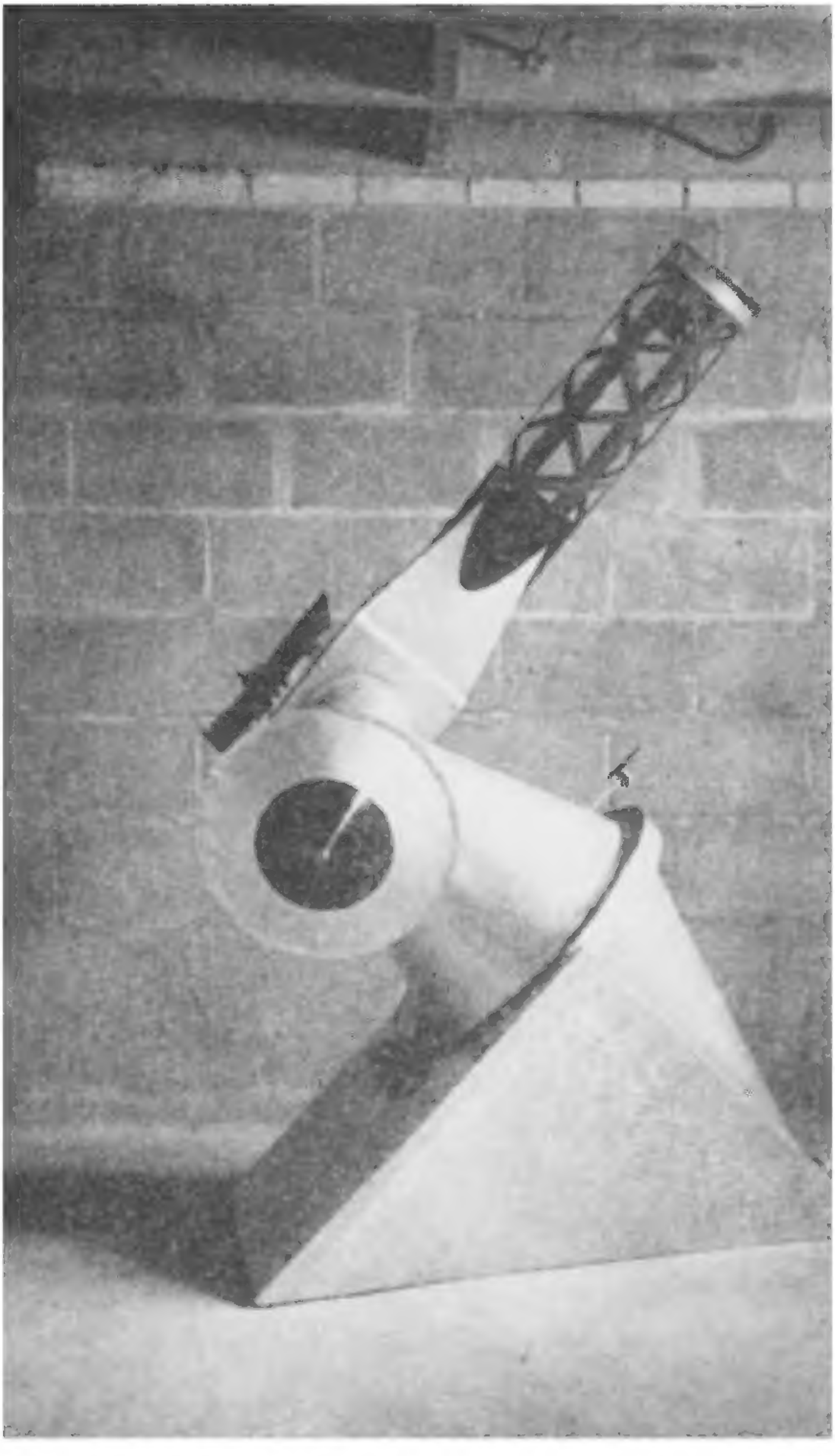
CONSTRUCTING AN ASTRONOMICAL TELESCOPE

G. MATTHEWSON



6-in. Newtonian reflector

Constructing an Astronomical Telescope

BY

G. MATTHEWSON

SECOND EDITION

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PREFACE

This short work is written primarily for the benefit of those interested in astronomy who wish to possess an instrument capable of extending their exploration of the universe without involving a large capital outlay.

A secondary object is to introduce to those seeking a hobby demanding patience and extreme accuracy, the fascinating art of telescope-mirror making. By accuracy I do not mean the " tenth thou." of the mechanical engineer; for a mirror to be of service it must be worked to an accuracy of something like ten millionths of an inch. Impossible for an amateur? Not a bit. I have made several mirrors ranging from 6 in. to 12 in. in diameter, and being an accountant by profession I cannot lay claim to possessing any special mechanical skill.

If you are interested, digest the following pages and then go to it. The production of your first mirror will be its own reward.

January, 1947 G. MATTHEWSON.

PREFACE TO THE SECOND EDITION

The demand for a reissue has made it possible to add a chapter on " An Inexpensive Mounting ".

February, 1955

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CHAPTER I

Types of Telescopes

Figs. 1, 3, 4, and 5 show the optical layout of the various types of telescopes in use, and it may be as well to start by describing the principles involved and the respective merits and demerits of the two main types—the *refractor* and the *reflector*.

The Refractor

As will be seen from fig. 1, light from the object being observed is brought to a focus by means of a large lens, known as the objective lens, and is examined and magnified by means of a smaller lens or combination of lenses known as the eye-piece, or ocular lens. If the objective lens were made from one single piece of glass as in the case of an ordinary magnifying glass, it would be found that the object under observation was surrounded by strong prismatic colours. This is due to the fact that the various coloured rays comprising sunlight are not all refracted to the same degree on passing through glass, and therefore are brought to a focus at varying points along the optical axis of the lens (see fig. 2). In order to remedy this defect the objective lens is built up from two or more glasses possessing special optical properties, and so designed as to bring the various rays to a common focus.

The Reflector

Fig. 3 shows the Newtonian type of *reflector*, and this is the type described in this book. The rays of light in this telescope are brought to a focus not by means of a lens, but by reflection from a silvered concave mirror. As the head of the observer would obstruct the incoming rays of light if the eyepiece were placed at the point of focus, the converging rays

are reflected to the side of the telescope tube by means of a prism or silvered glass diagonal.

Figs. 4 and 5 show the Cassegrainian and Gregorian types of *reflectors* respectively. In the Cassegrainian a small convex

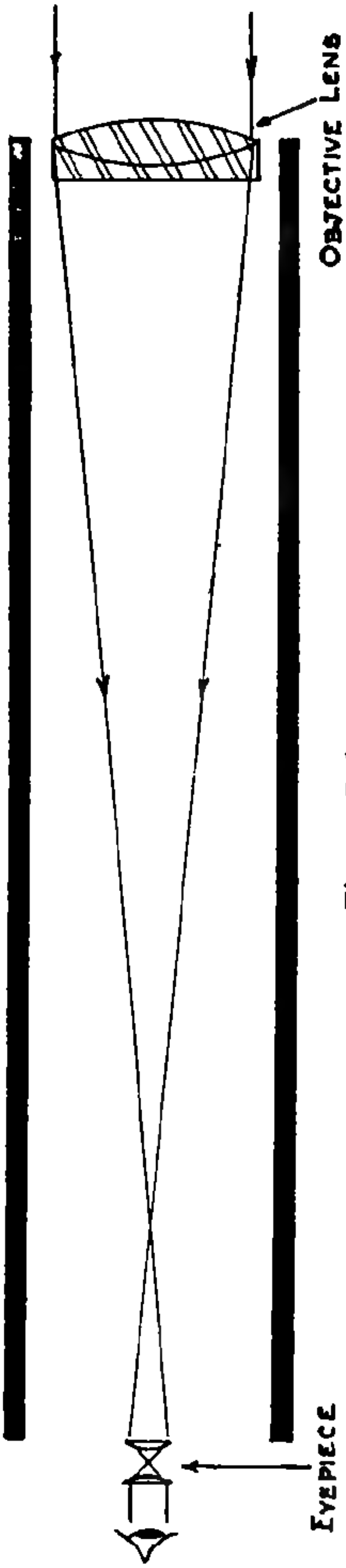


Fig 1.—Refractor

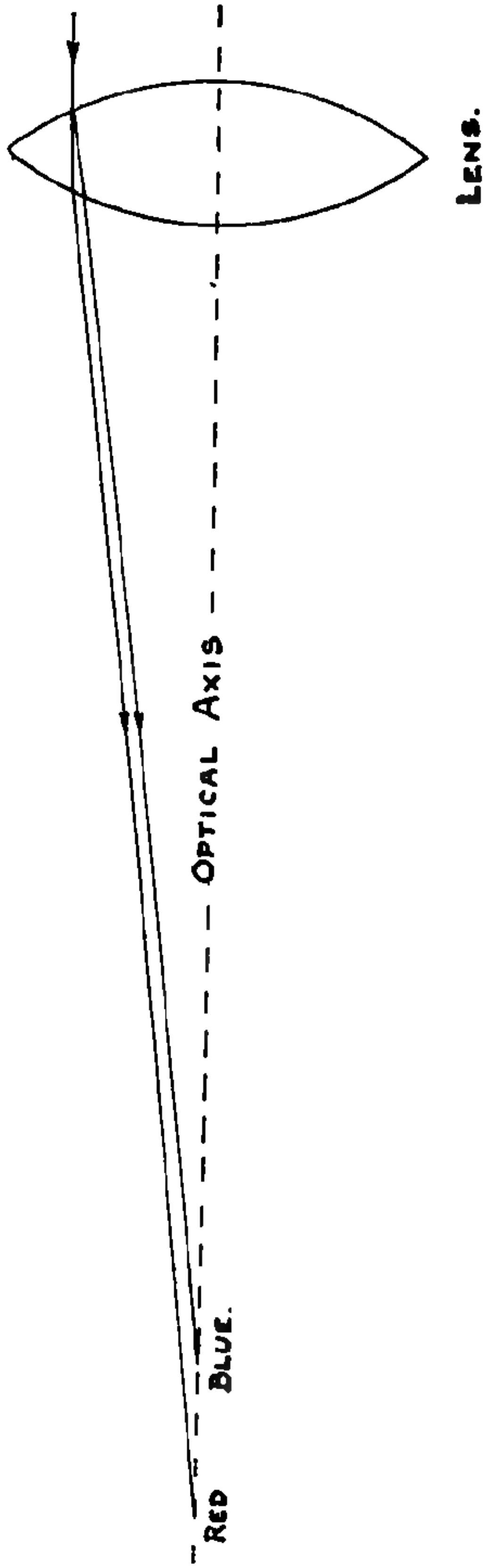


Fig. 2.—Chromatic aberration

mirror is placed just in front of the point of focus, so that the rays are projected back towards the main mirror and pass through an aperture in this mirror to the eyepiece. The

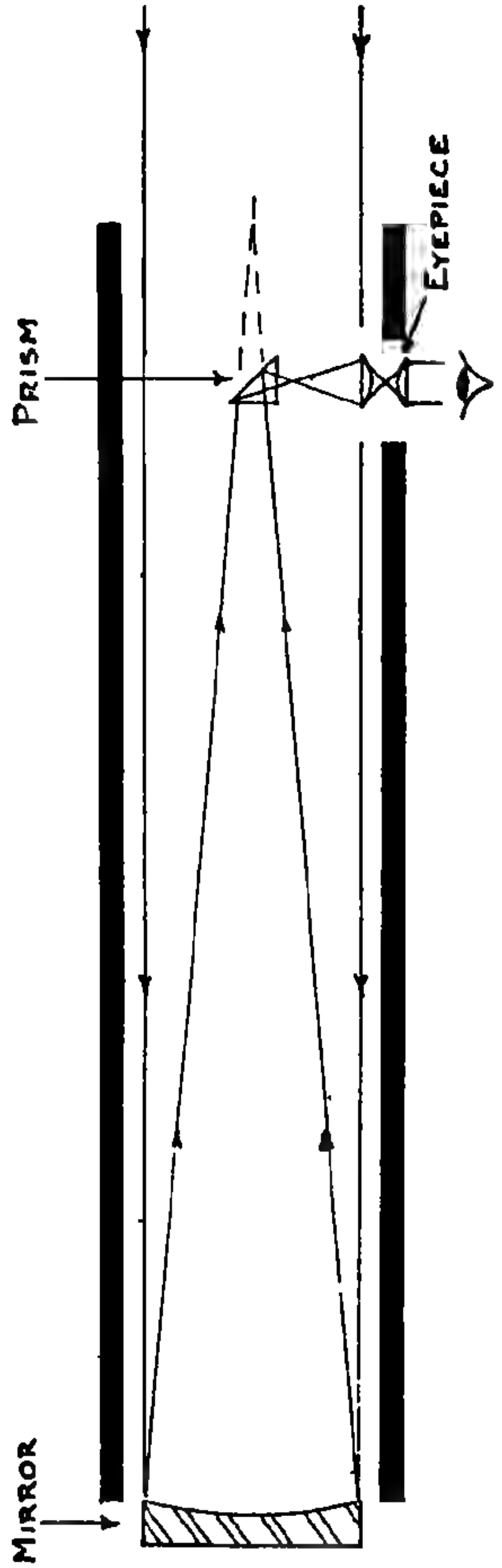


FIG. 3.—Reflector (Newtonian)

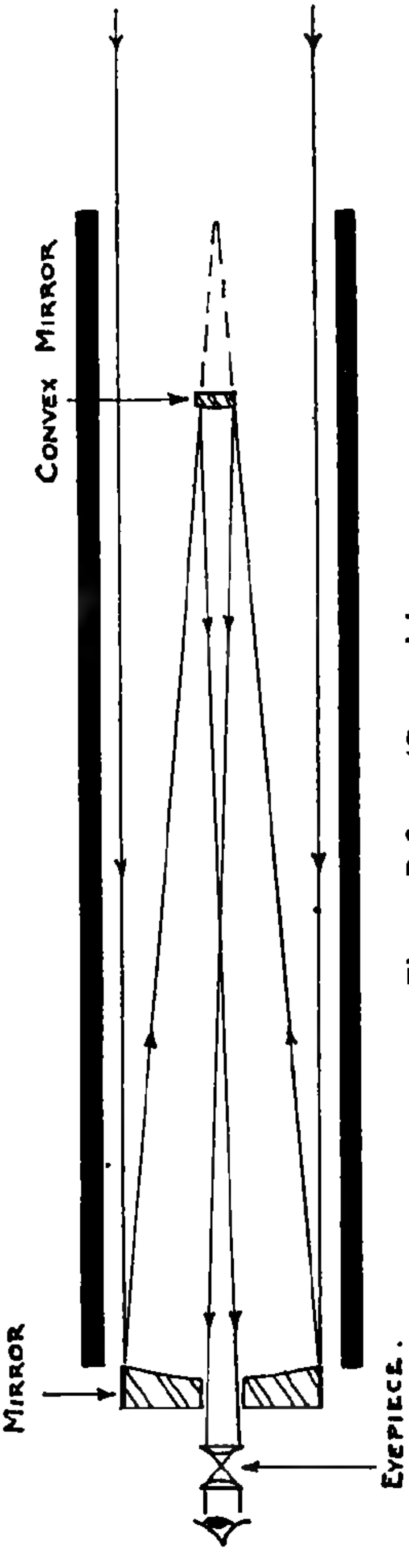


FIG. 4.—Reflector (Cassegrainian)

Gregorian is similar in principle, a concave mirror being placed just beyond the point of focus. Both of these types have the advantage of greatly increasing the focal length of the main mirror (which will result in a greater power of magnification) without having an unwieldy length of telescope tube. To avoid drilling a hole in the main mirror, it is possible to use a prism placed just in front of the mirror and deflecting the rays at right angles as in the Newtonian. The figuring of the additional optical surface in the form of the convex or concave secondary mirror demands some skill and experience. As we are mainly concerned with simplicity of construction it is obvious that the Newtonian *reflector* presents the least difficulties, inasmuch as there is only one optical surface to work, and as the rays of light do not pass through the glass, but are reflected from the surface, there is no need to use glass possessing special optical qualities. It may, in fact, be said the glass is merely a solid support for a very thin film of silver.

The disadvantage of the *reflector* is that the silver, being exposed to the air, is subject to deterioration, and has to be renewed at intervals otherwise there is a considerable loss of light-gathering power due to the tarnishing of the film. There is also a further slight loss due to absorption at the reflecting surface. A more recent process, consisting of depositing a film of aluminium in place of silver, does much to overcome these defects, but the carrying out of this work is beyond the capabilities of the amateur on account of the expensive apparatus used, and will not be described here.

The main advantage of the *reflector* is the absolute freedom from chromatic aberration, i.e. the prismatic colour effect mentioned in the description of the *refractor*. Other points in its favour are that it is more compact than the *refractor*, and gives really excellent definition. Much has been written regarding the respective merits of the two types of telescopes but, for our purpose, the production of a first-class instrument with the minimum cost both in material and labour, the *reflector* stands supreme

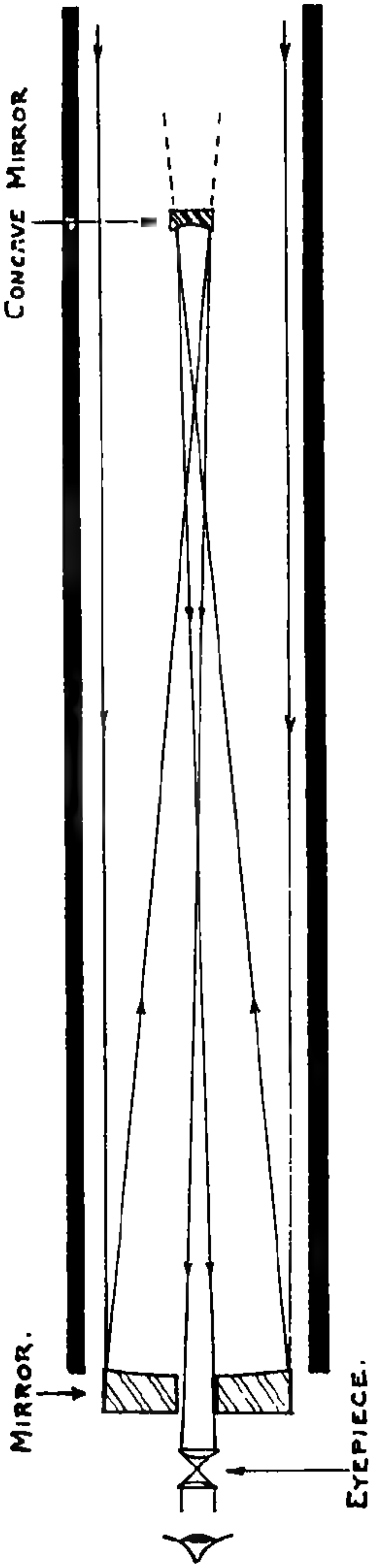


Fig. 5.—Reflector (Gregorian)

CHAPTER II

The Mirror

Before starting to describe the method of making a concave mirror, a brief description of its function in the telescope may prove of value to the reader in order that he may understand the object of each stage in the process of making the mirror.

It has been stated earlier that the rays of light are brought to a focus by means of reflection from a silvered *concave* mirror. Fig. 6 demonstrates the manner in which this is done, but there is the question of the shape of the concave part of the mirror to be decided—will it be, in section, part of a circle, an ellipse, a parabola, a hyperbola, or any of the numerous intermediate curves? The answer is that there is one curve and one curve only which will suit our purpose—the *parabola.* We are all familiar with the reflector used in a motor-car headlamp, which is of paraboloidal construction, where the rays from a lamp placed at the point of focus are reflected in the form of a parallel beam. Our *reflector* telescope embodies the same principle, but in reverse—the parallel rays of light entering the telescope are reflected to the point of focus. How are we to obtain this paraboloidal surface? First of all, take a look at fig. 7, which shows the difference between a circle and a parabola. When it is pointed out that the distance between point A and point B in the case of a 6-in. diameter mirror is approximately five-millionths of an inch, it will be appreciated that if we can find a method of grinding out our mirror to a spherical section it should not be too difficult to deepen the curve to that of a paraboloid. That is precisely the method we shall adopt, and although the process used to grind the mirror is simplicity itself, the resulting surface will be a true sphere—it can't be anything else. To deepen the

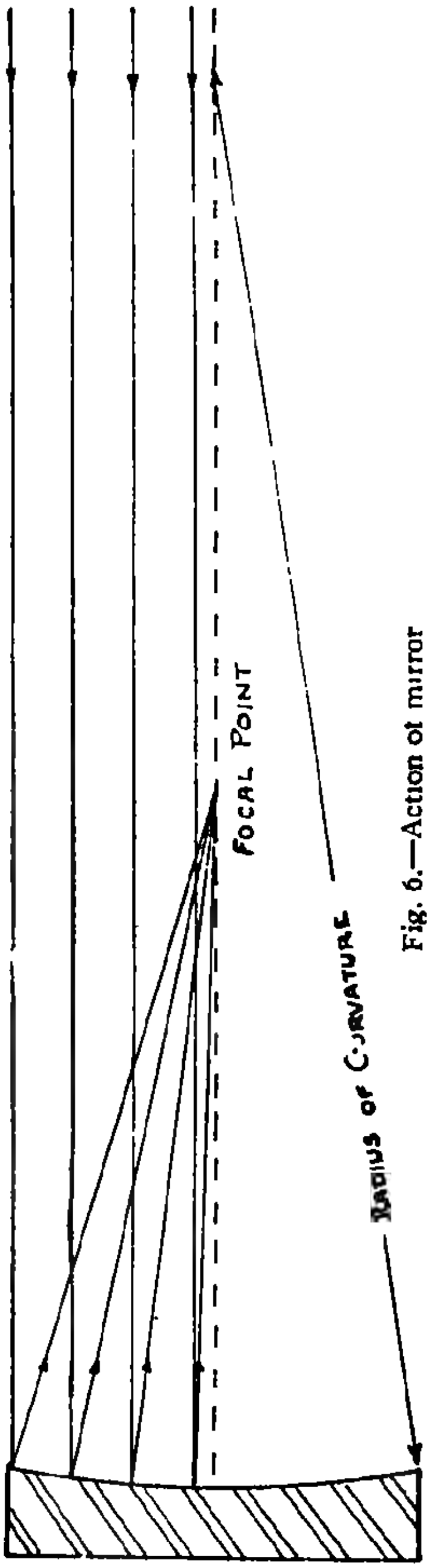


Fig. 6.—Action of mirror

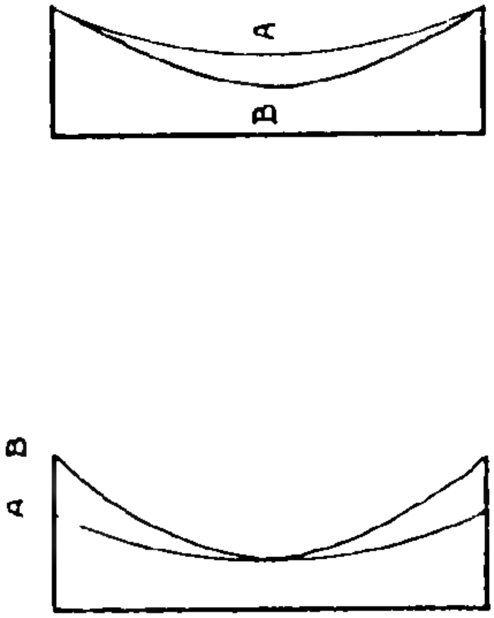


Fig. 7.—(A) Circle. (B) Parabola

surface to a paraboloid we shall not be able to do this by grinding as the amount of glass to be removed is so slight, but this will be taken care of when we have the mirror polished.

How the Glass is Ground to Shape

The job of grinding out a flat disk of glass to a curved surface may at first sight appear to be a formidable task involving elaborate machinery, but actually it is most efficiently performed by hand, except in the case of very large mirrors, where the great weight involved renders hand work impracticable, and the method is as follows. Two rough-cut circular disks of plate-glass are first obtained of a diameter slightly larger than that desired for the mirror, to allow for grinding the edges smooth. After grinding the edges smooth and to size, and making a slight bevel on the circumference, one of the disks is fixed securely to a stand or bench as in fig. 8, and a thin paste of carborundum and water placed on the upper surface. This piece of glass is known as the " tool ". The other piece of glass, which will form the finished mirror, is then placed on top of the tool, and worked backwards and forwards so that the centre of the top disk moves to a position approximately at the edge of the lower disk when the end of the stroke is reached. This backward and forward motion is repeated, with each stroke being made along a different diameter of the tool as in fig. 9D.

Fig. 9A and 9B portray what takes place during this action. When the mirror is at the end of its stroke the greatest grinding action, due to the weight of the top disk, is at the centre of the mirror and the edge of the tool, and therefore if the grinding is continued long enough over the whole surface it will be found that the tool becomes convex and the mirror concave (see fig. 9C). The initial hollowing out is done with a coarse carborundum until the approximate depth is reached, which will give the required focal length of the mirror, and the same process is then repeated with progressively finer grades of carborundum until the surface resembles a very fine frosted glass which is almost transparent. The final polish is obtained by coating the tool with pitch and substituting rouge and water

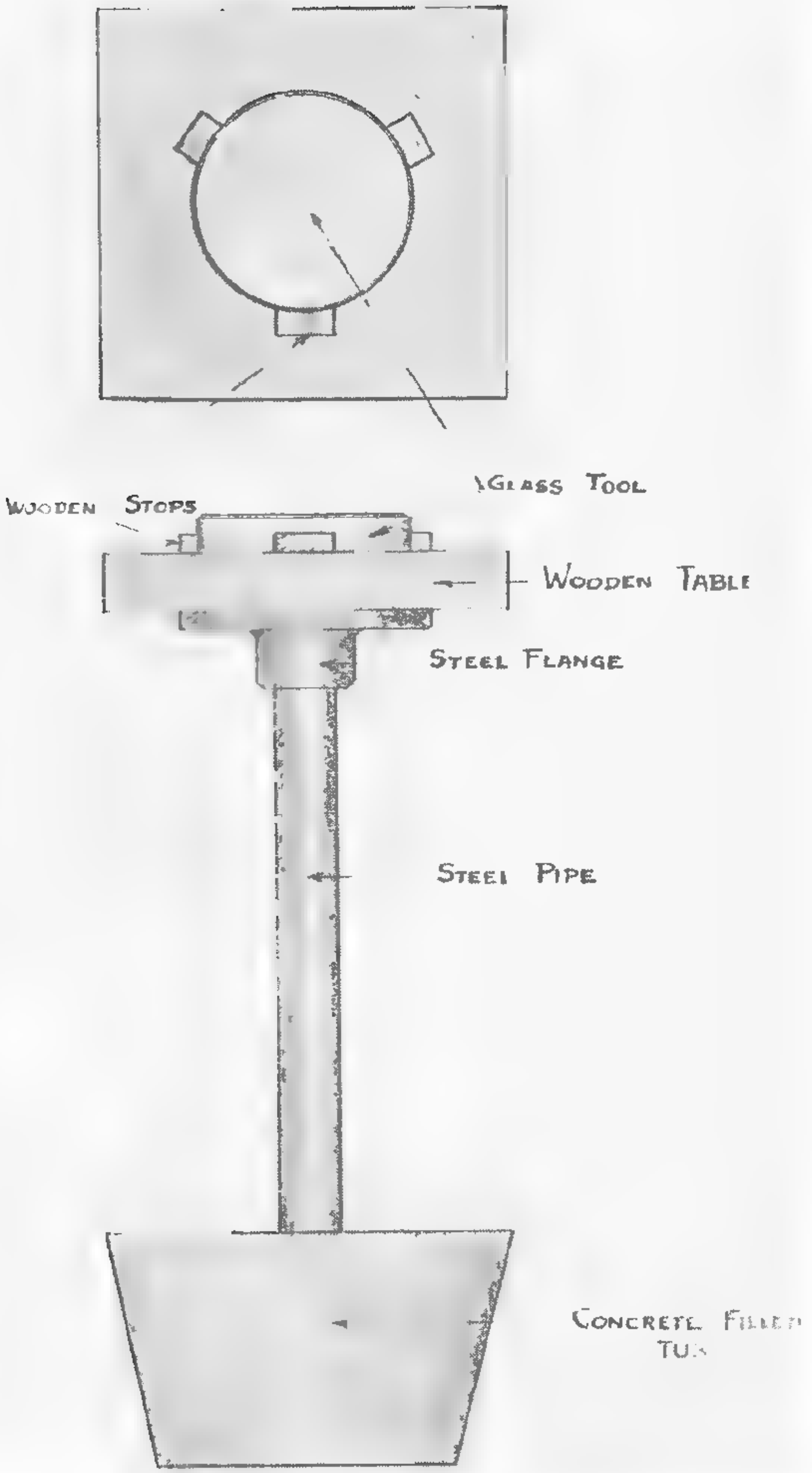


Fig 8 —Grinding and polishing pedestal

for the carborundum and water, and working the mirror backwards and forwards in the same manner as for grinding. If all the operations have been carried out with care the result will be a polished surface of perfect spherical section. Then

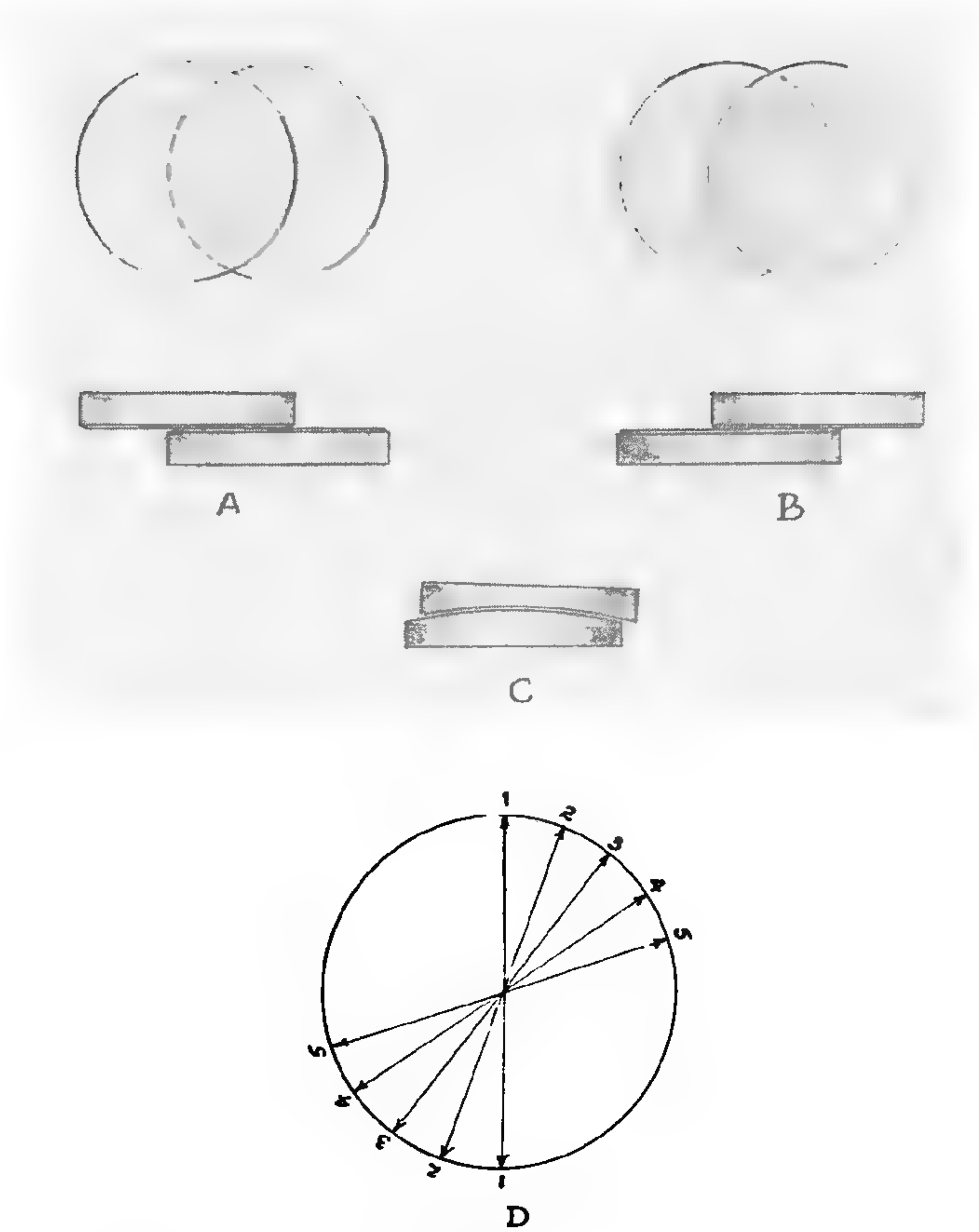


Fig. 9

A. First half of stroke. B. Second half of stroke. C. Ultimate shape of tool and mirror. D. Order of strokes

all that remains to be done is to deepen the curve of the mirror to a paraboloid by means of the same polishing process —and that is the part of the operation which calls for the greatest patience and skill.

Getting Down to Work

Having got an outline of what is before us we can now proceed to plan out the workshop and make a list of the tools and materials that will be required. First of all, the workshop. Glass grinding and polishing can be a very messy business, and it is therefore advisable to carry out the work where blobs of carborundum, ground glass and water, and the deep red stain of rouge will not be commented upon. The dining-room table is hardly satisfactory from this point of view. Another essential is that the workroom should be free from dust. This is not so important in the first stages of grinding, but when we get down to the fine grinding, and particularly when we start to polish, it is imperative that no stray particles of carborundum or other dust should be allowed to settle on the tool. It is very annoying after having spent some hours on polishing only to find that the mirror is covered by minute scratches caused by particles which have settled on the tool, and which can only be removed by reverting back to fine grinding.

It will be seen then, that a shed in the garden or an unused garage would meet our requirements. Having decided upon the place where we are going to work, the next step is to find a suitable support for the tool. As some considerable pressure is placed upon this when working it needs to be somewhere firm. A rigidly constructed bench will serve our purpose, but the ideal is a specially constructed stand as shown in fig. 8. The heavy concrete base gives ample stability, and it has the added advantage of portability as it is a simple matter to roll the stand to any position. It also enables the operator to walk round the tool whilst grinding and polishing, and thereby eliminating the necessity for constantly changing the position of the tool. This will have to be done if the tool is fixed to a bench.

Now let us consider what materials will be required. These are very few and can readily be obtained. The following is a fairly comprehensive list:

1. Two disks of glass. One for the tool and one for the mirror.
2. Carborundum. Several grades will be required, and the writer has found the following to be a good working range. Nos. 80, 220, 320, 400, 500 and 600. Half a pound of each will be sufficient for several mirrors.
3. Pitch. This is a black substance obtained from the distillation of coal, and possesses the unique property of acting both as a solid and a fluid. It can be fractured by a sharp blow, but can be readily bent by steady pressure, and if a lump is placed in a container such as a tin or box and left for some time, it will be found to have " flowed " and covered the bottom of the container. One or two pounds will be ample and can be obtained from any oil shop.
4. Turpentine. Pure American turpentine should be obtained as the turpentine substitute is useless for our purpose. Half a pint will be plenty.
5. Beeswax. A quarter to half a pound.
6. Half a pound of optical rouge.
7. Half a pound of flour emery.
8. A supply of cotton-waste and cotton-wool for " mopping-up " operations.

For convenience in use and to avoid contamination of the various grades of carborundum, a small salt-sprinkler should be purchased for each grade, and the grade number marked clearly on the outside.

Glass Disks

As previously mentioned the glass for the mirror need not be of special optical quality, but it should be well annealed and free from bubbles near the surface, and in order that it shall not flex under its own weight, the thickness should be at least $\frac{1}{8}$ the diameter. For a first attempt I would recommend a diameter of 6 in., as this is a very convenient size to handle

and will not take too long to work. It should be borne in mind that the amount of work on a mirror does not vary directly as to the diameter, but as to the surface area. A mirror of 6 in. diameter has only about half the area of an 8-in. diameter mirror.

To start on our 6-in. diameter mirror we shall therefore require two disks of plate-glass, 1 in. thick. These can be obtained rough-cut to size, and the preparatory work of grinding the edge smooth will give the operator a good idea of the cutting speed of carborundum and how to judge the progress of grinding by the "feel" and "sound". The writer found that second-hand port-hole glasses were excellent material for the first attempt.

After experience has been gained on the first mirror it may be desired to produce a more professional-looking mirror, in which case selected plate-glass or Pyrex can be used, but remember that the success of the finished job will depend not so much on the quality of the glass but the skill of the operator.

To edge the disks it will be necessary to arrange some sort of spindle for rotating the glass, and a drawing of one made by the writer is given in fig. 10. This is made from a cycle crank bearing and pipe fittings, and makes a very sturdy job. If you have access to a lathe so much the better, as a lot of hard work will be eliminated. Pitch is used to cement the disk to the face plate and the operation is carried out as follows. Warm the glass disk by immersing it in warm water for a short period (not too warm, or you may crack the disk —about as hot as the hand can bear), and after drying, smear the face with a thin film of turpentine. While this is being done, have some pitch melting in a saucepan over a suitable source of heat. Pitch gives off very pungent fumes when being melted, so it is advisable to do this out in the open; there is also a danger of it catching fire if overheated, so keep a lid or piece of sheet iron handy with which to smother the flames. When the pitch is completely molten pour a small quantity on to the face plate, sufficient to cover the surface with a layer about $\frac{1}{16}$ of an inch thick. Then press the glass

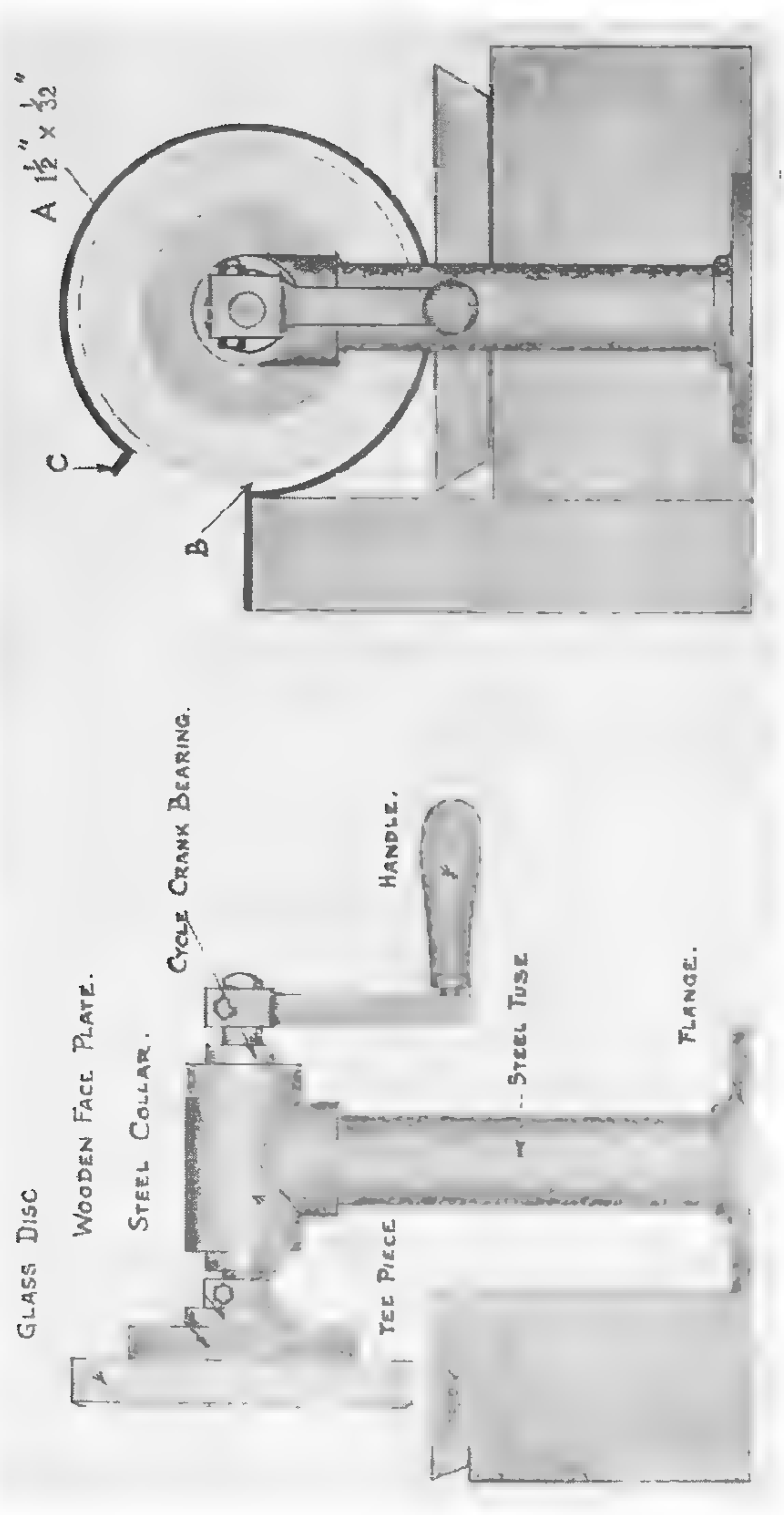


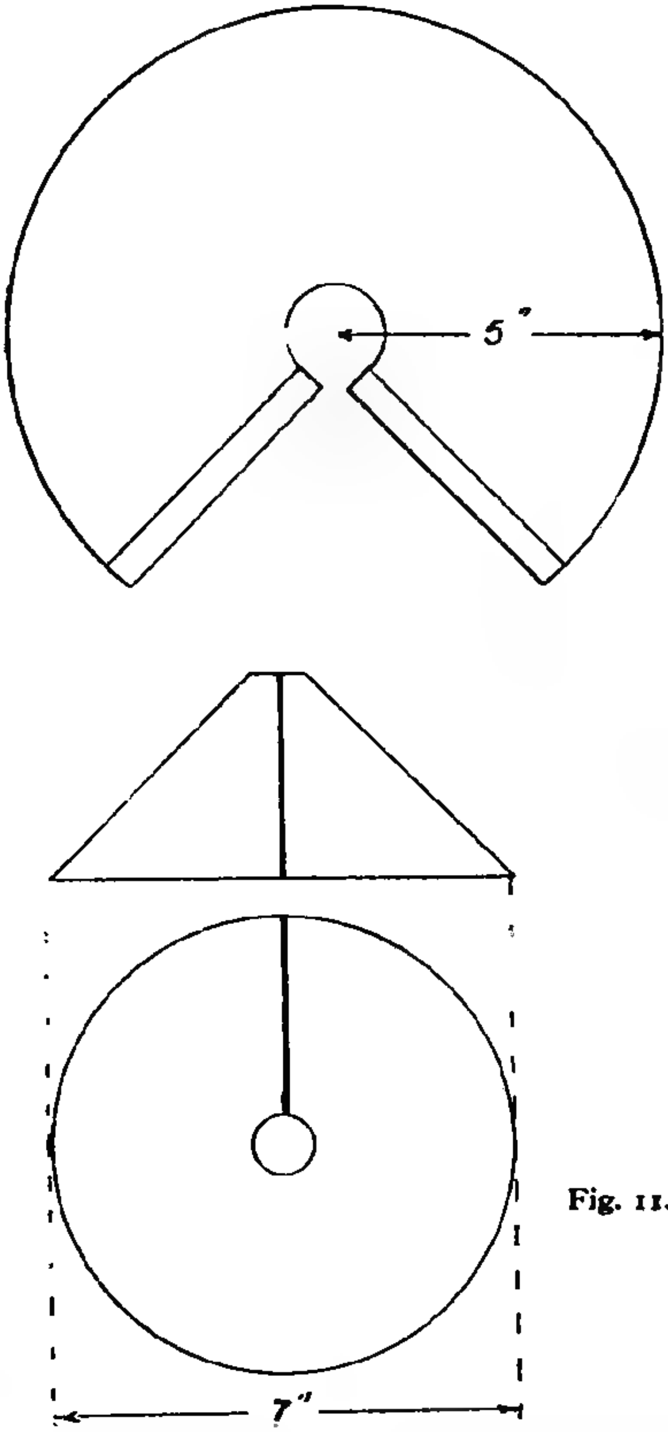
Fig. 10.—Spindle for grinding edge of discs

disk into contact with the pitch and refix the face plate on to the spindle. Whilst the pitch is still warm, centre the glass disk by rotating the spindle and pressing on the edge of the disk until it revolves evenly without any wobble or side play. When this has been attained remove the face plate from the spindle and lay it face downwards on a flat surface so that the relative positions of the plate and glass will not be disturbed, and allow them to cool down to room temperature.

When you are certain that the disk is firmly cemented to the face plate, remount on the spindle and attach the sheet-iron band (A, fig. 10). Pour a small quantity of No. 80 carborundum and water between the band and the disk at B, and whilst revolving the spindle press down on the end of the band at C to bring it into contact with the glass. As soon as contact is made you will hear the harsh grinding noise of the carborundum grinding away the glass, and some resistance will be felt in turning the spindle. At the same time the water-carborundum mixture will begin to get milky, and eventually will become a light grey colour due to the admixture of particles of ground glass. As soon as the harshness of the grinding diminishes, add some more carborundum and water, and continue revolving the spindle with a steady light pressure on the sheet-iron band. After a period examine the edge of the disk and see how the grinding is progressing. The "high spots" will be wearing down, leaving hollow depressions, and these must be completely ground out so that the whole of the edge of the glass presents a coarse ground surface. Never let the surfaces in contact get dry, otherwise the friction generated may heat the glass sufficiently to detach it from the face plate. The spent liquid which drops into the tray may contain quite a quantity of carborundum which has not been broken down completely, so from time to time some of this can be scooped up and used in place of fresh carborundum. When you are satisfied that all hollows on the edge have been ground out, give the glass and sheet-iron band a thorough wash down with plenty of water and finish off the surface with a finer grade of carborundum—say No. 220.

All that remains to be done now is to make a bevel of

about $\frac{1}{8}$ of an inch on one edge. This is most readily done by means of a sheet-iron or zinc cone, as shown in fig. 11. No. 220 carborundum should be used for this operation as the



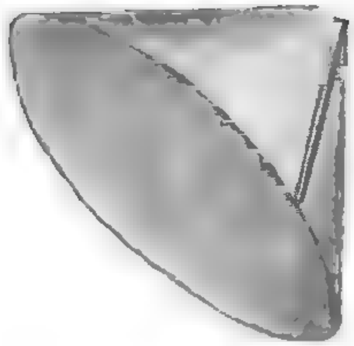


Fig. 11.—Construction of cone for making bevel on glass discs

grinding action is quite rapid and there is less likelihood of the edge chipping. If the glass disk has been fairly accurately rough-cut to size, about one-half to three-quarters of an hour should suffice to grind the edge smooth, and about a quarter of an hour will produce the required bevel.

Both disks should be treated in the same way. Some operators emphasize that both disks should be exactly the same diameter, but the writer has not found this to be necessary and provided they are within a $\frac{1}{4}$, or even $\frac{1}{2}$ an inch, no trouble will be found in producing a good mirror. If you find, after edging your disks, that one is smaller than the other, use the smaller of the two as your tool, as there is then less likelihood of forming a turned-down edge on your mirror.

To remove the glass disk from the face plate, lay the disk face downwards on a table or bench and give the edge of the face plate a sharp blow with a wooden mallet, when it will be found that the two part company quite easily. For this reason, care should be taken when working to avoid any sharp knocks, otherwise you may separate the disk from the face plate with disastrous results. The pitch remaining on the glass can be removed with turpentine.

CHAPTER III

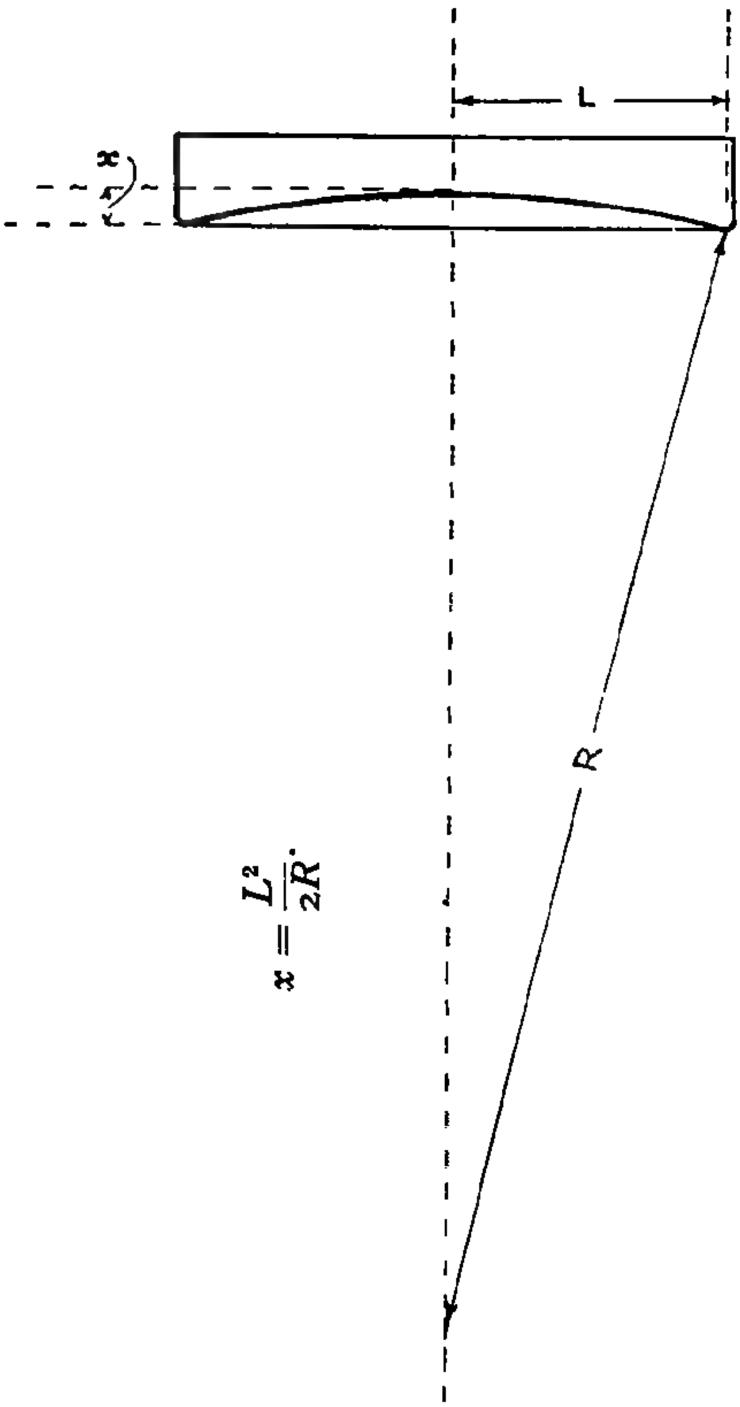
Grinding

In all telescopes, unless they are designed for some special purpose, there is a common ratio between the diameter of the mirror or lens and the focal length. In the case of a *refractor* the focal length is usually about twelve times the diameter of the objective lens, and in a *reflector* the focal length is about eight times the diameter of the mirror. This ratio is determined by the optical requirements of the telescope and its mechanical construction. The average general-purpose telescope has the above-mentioned ratio between diameter and focal length, and this is expressed as $f/12$ or $f/8$, as the case may be. Those of you who have dabbled in photography will be familiar with this expression, as it is also used in connexion with a camera lens.

For our 6-in. diameter mirror, therefore, we shall require to produce a curve which will focus the parallel rays from a distant object to a point 48 in. from the surface of the mirror. Looking at fig. 6, it will be seen that if the rays striking the mirror are *parallel*, then the focal length will be exactly one-half the radius of curvature. I particularly stress the word parallel, because when we come to test our mirror the light source will be at the radius of curvature, and the rays, not being parallel, will be reflected to the same point as the source of light. This is demonstrated in fig. 17 (p. 33). It will be seen on reference to fig. 12, that the depth to which the centre of the mirror has to be ground out is 0·047 in., so that the amount of work involved is not very considerable.

Having selected the better of the two glasses for the mirror (i.e. the one most free from air bubbles near the surface), a wooden handle (fig. 13) is cemented to the back with pitch in the same manner as we fixed the glass to the face plate of

the turning spindle. This handle serves a double purpose. Firstly it enables us to get a good purchase on the mirror, and secondly it prevents the heat of the hands causing unequal



$$x = \frac{L^2}{2R}.$$

Fig. 12.—To find depth of curve

expansion of the glass and consequent distortion. Any such distortion would be of a very small magnitude, and would not have any deleterious effect during the rough grinding and even during the early stages of fine grinding, but it would produce some very undesirable effects during the polishing and figuring.

The other glass which is to be used as the tool is fixed to the bench or grinding pedestal as in fig. 8, and a small quantity of No. 80 carborundum and water is placed on the upper surface. The mirror is then placed on top, and grinding is started by pushing the mirror backwards and forwards over the tool as in fig. 9, using a firm but not too heavy pressure, and with each stroke being made along a different diameter of the tool. At the same time the mirror is turned through ten or twenty degrees in the hand after every stroke, in a direction opposite to that in which the mirror is being worked over the tool. As the main object at this stage is to remove

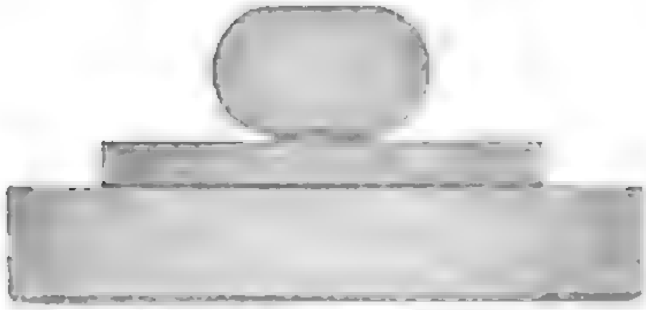


Fig. 13.—Handle for working mirror

as much glass as possible from the centre of the mirror, the full stroke can be used, but during the later stages of grinding it will be necessary to shorten the stroke to two-thirds or one-half of the full stroke in order that the curve will be a true sphere. If the tool is mounted on a bench it will be necessary to revolve the tool through a small angle from time to time, which will give the equivalent effect of walking round the pedestal. The object of these various motions is to get an even grinding action over the whole area of the mirror and tool so that the resultant surface is a true surface of revolution. As we proceed with the grinding we notice the same effects as those observed during the grinding of the edges of the disk, i.e. the harsh initial grinding noise which gradually becomes smoother as the carborundum particles are broken down, the formation of a light grey sludge between the surfaces due to the admixture of ground glass particles, and the gradually increasing resistance caused by the drying up of the carborundum-water mixture. When it is felt that the grinding action

is slackening owing to the breaking down of the carborundum, the mirror should be lifted off and fresh carborundum and water sprinkled over the tool. As a matter of interest, lift off the mirror after grinding for about ten minutes, and swab down the surfaces of the two glasses with a piece of waste and plenty of water. It will be found that the centre of the mirror has been ground mostly, tapering off towards the edge, which may still be transparent for a distance of perhaps 1 in. from the edge. The tool, on the other hand, will be the converse of this—the outer portion being ground and the centre still more or less transparent. If this is the case, you can rest confident that all is going well and continue with the grinding. If you find that there is no appreciable difference in the grinding of the mirror and the tool, it is probably due to too fast a stroke or too much pressure on the mirror.

As we are working to a definite radius we shall want to know when the curve has been deepened sufficiently, and in order to find this out we can use one of three methods. Firstly, the depth of the curve can be directly measured by means of a spherometer, an instrument specially designed for this purpose, but as it is unlikely that the reader will have one in his possession, and in view of the expense involved in purchasing such an instrument, I will go no further than mentioning it as a means of finding the depth of the curve on the mirror. The second method is to make a brass or zinc template of the required curve and to match this against the surface of the mirror until it fits snugly. The template is quite easily made from a piece of sheet brass or zinc about 6 to 8 in. long and 3 to 4 in. wide. This is firmly secured to a long bench, or on the floor, and a wooden or steel bar provided with a pivot and scriber spaced 96 in. apart (the required radius of curvature) is used to mark off the curve on the brass or zinc. This is then cut along the scribed line and carefully filed true.

The third, and possibly the easiest method, is by direct observation of a light reflected from the surface of the mirror. Although the ground-glass surface is non-reflecting, it can easily be made so by wetting with water, and this will remain on the glass long enough for our test. The wetted glass is

placed on edge at about eye level and, standing in front of the mirror, an electric torch held to one side of the head is directed so that the rays are projected to the mirror and reflected back to the eyes. If the torch is moved from side to side it will be found that the reflection moves in the same direction so long as the light is inside the point of focus, which in this case is also the radius of curvature. If the torch is moved from left to right the reflected image will also appear to move from left to right. If, however, we walk backwards until the light is *outside* the point of focus, the reflected image will appear to move in the opposite direction to that moved by the torch. If the torch is still moved from left to right the reflection will move from right to left. The point where this change-over takes place will be the radius of curvature of the mirror. It may be a little difficult at first to judge when the point of change-over has been reached, but with practice it is possible to gauge the distance to within an inch or two, and that will be quite accurate enough at this stage as in any case we have to stop grinding with No. 80 carborundum as soon as the radius is within ten or twelve inches of that desired, and continue the grinding with the next finest grade. If you should find that you have been over-industrious in the rough grinding and the radius of curvature is under the 106–108 in., it is a simple matter to remedy this by transposing the position of the mirror and tool and continue grinding with about half-stroke for a short period. The allowance of ten or twelve inches in the radius is made on account of the fact that the radius is still further shortened during the fine grinding, and at the last stage the radius will be found to be reasonably accurate if this margin is allowed.

Incidentally, if you use the above visual method of finding the radius it is advisable not to let your neighbours see you walking backwards down the garden waving a lighted torch from side to side in broad daylight—they may have doubts as to your mental stability.

When the mirror has been ground to the correct radius we shall be ready to change over to the next finest grade of carborundum. To do this we must clean off thoroughly all

traces of the No. 80 carborundum from the tool and mirror. When I say thoroughly, I mean thoroughly. Use plenty of water and waste for cleaning off not only the surfaces of the glasses but the edges as well, and scrub the bench or table vigorously to remove any stray particles of the coarse carborundum. Wash your hands and clean out under your finger-nails; it's surprising how a grain of carborundum can hide away only to appear at a later stage when it is not wanted. When you are satisfied that everything is spotless and free from all traces of the grade of carborundum you have been using, go over the whole lot again. The business of cleaning off one grade of carborundum before starting with another

Fig. 14.—Relative cutting depths of carborundum

cannot be over-emphasized. The sketch shown in fig. 14 gives the relative depths of cut made by the various grades of carborundum, and it will be realized from this that a stray particle of say No. 220 dropped on the tool when you are working with No. 500 will result in a scratch over the face of the mirror, which can only be removed by reverting back to the No. 320 stage. Any attempt to try to get rid of such a scratch during the polishing process would be doomed to failure. You would die of old age before this could be accomplished.

The grinding out to the rough radius of curvature will take you from half an hour to an hour's grinding. It is of the utmost importance during the next stages of grinding that the pits made by one grade of carborundum are completely removed by the next grade. There is no use cutting one stage short in the hope that any deep pits left will disappear if you lengthen the last stage—they just won't. For this reason I would advocate that each stage of grinding should be carried out for one hour; and I mean one hour of actual grinding.

Keep a record of the time spent on each grade, and if you stop to admire the scenery or smoke a cigarette, or for any other reason, knock that time off your record. In this game there are no short-cuts—it's all a question of patience and conscientious work, and the only grease you can use is elbow grease

Now you can carry on with the No. 220 carborundum in exactly the same manner as with the No. 80, but shorten the stroke to two-thirds. You will find that the mirror and tool now begin to cling and are harder to work, and it may be necessary to add a few drops of water now and again to ease the situation. It will be found that each application of carborundum and water will be "worked out" after about five minutes' grinding, and a fresh supply should then be added. By this time you will have had sufficient experience to tell by the "feel" whether the carborundum is cutting or not. To apply the finer grades of carborundum to the tool, it is sufficient to wet the tool and mirror well and sprinkle the carborundum thinly over the surface of the tool direct from the salt-sprinkler container.

One word of warning. Keep your eye on the bevel. If this has been made wide enough you will not have any trouble, but if you have skimped the operation you may find that it has been ground away by the time you come to the final grinding. If that should happen, there is no need to mount the mirror or tool on the spindle. Place the glass securely, face upwards, on a bench and work the cone on top with the hands, turning it backwards and forwards through 90°.

When you have completed the full hour of grinding with No. 220, wash down as before, and repeat the grinding with No. 320, then 400, 500 and 600. The last three grades should be worked with one-third stroke.

In the fine grinding you will find an ever-increasing tendency for the glasses to stick together, and on this account the surfaces in contact should not be allowed to get too dry. If the mirror should seize on the tool a few drops of water placed round the edge may be sufficient to ease them apart, but in extreme cases it may be necessary to resort to putting them

in warm water, or even prising them apart with a small hardwood wedge. The fine grinding entails quite a bit of energy, and if you should " knock off for a breather " never leave the two glasses in contact, otherwise you may find when you come to resume work that they are firmly held together, and some considerable time will have to be spent in getting them apart.

The No. 600 carborundum will give us a surface sufficiently fine to enable it to be polished, but it is worthwhile to give a final grinding with flour emery. The pits or grooves left by emery are shallower and rounder than those left by carborundum, and consequently the surface is more readily polished. About a quarter of a pound of flour emery is placed in a jam-jar or similar receptacle and three parts filled with water. The mixture is well stirred and left to stand for half an hour to an hour. The top should of course be covered to prevent any dust particles settling in the jar. The slightly cloudy liquid which is left when the emery has settled after the specified time is then carefully decanted or syphoned off into another clean jar and allowed to settle. The very fine emery which results from this second settling is then used in the same way as the fine carborundum. About half an hour of grinding with this emery will be sufficient to give a really good surface.

It is as well during the fine grinding to examine the mirror from time to time with a strong lens, or better still a microscope. The edge of the mirror should be examined as this is the part which is ground out last, and if the pits appear to be of uniform size with no " left-overs " from the previous grade, then it may be considered safe to change over to the next finer grade. Too much reliance should not be placed on this visual method, however, as it is rather difficult even after some experience to determine when all the pits from the previous grade have been levelled out. It is safe to say that if you conscientiously give one hour of actual grinding to each stage, there is no reason why your mirror should not take on a perfect polish.

The next stage is to get our mirror polished.

CHAPTER IV

Polishing

To the uninitiated the polishing of glass has always been a bit of a mystery, and much has been written on the theory of the mechanical process involved in polishing. Although the operational method of polishing is essentially the same as for grinding, the action which takes place between the two surfaces in contact is not the same. In grinding, the particles of carborundum are rolled between the two surfaces and crush or fracture the glass, so that no matter how fine the carborundum the surface will always present a ground or frosted appearance. In polishing, however, the tool is coated with a layer of pitch, which presents a yielding surface, and the particles of rouge bed themselves into this surface, and act more in the nature of a smoothing plane by cutting shallow rounded grooves. Rouge is an oxide of iron, very hard, but friable without limit, and as used for polishing glass is an extremely fine red powder.

The pitch used for coating the tool and forming the " lap ", as it is called, should be of such a consistency that if a strip about 3 in. long by ½ in. wide, and about ⅛ in. thick, is taken between the hands it will bend if pressure is applied evenly, but will snap if pressure is applied quickly. If the pitch is too hard it will have a tendency to scratch the glass surface, but on the other hand if it is too soft it will not give an even optical surface, and will result in a " turned-down edge " or similar defect.

Having completed the fine grinding, the tool and mirror are cleaned off thoroughly and the surface of the tool is given a smear of turpentine to enable the pitch to adhere firmly The pitch is then melted in a suitable container (saucepan,

old cocoa tin, &c.), and a sample poured on to a sheet of paper, and when cool is tried for consistency. If it is too hard, a small quantity of turpentine is added, and after stirring well together a further test is made. Don't add too much at a time as a very little turpentine makes quite an appreciable difference to the hardness of the pitch. If it is found that the pitch is too soft, this can be remedied by boiling for a short period, as this has the effect of distilling off the more volatile portion and leaving a harder residue. When the pitch is judged to be of the right consistency a small quantity (about half an ounce to a pound is a good proportion) of beeswax is added and stirred in to form a homogeneous mixture. The beeswax is not essential to forming a polishing lap, but it gives a rather better surface and renders the pitch more tractable. Pitch on its own has a tendency to chip and fly when being cut, and the addition of beeswax facilitates the trimming up and cutting of the necessary grooves.

If good-quality optical rouge is obtained it will be sufficient to mix it with water to a thin paste, when it will be ready for use, but if you have any doubt as to the quality of the rouge it should be treated in the same manner as the emery used for the final stage of fine grinding. Smear the face of the mirror with the rouge paste ready for forming the pitch lap. Having the tool mounted back on the grinding pedestal with the upper surface smeared with turpentine, pour on the molten pitch starting in the centre and working outwards, so that the whole surface is covered. Don't worry about it spilling over the edge of the tool as this can easily be cleaned up when it has set. Whilst the pitch is still molten, place the mirror on top with the rouge in contact with the pitch, and immediately start to work it about in all directions without applying any pressure. The object is to get a layer of pitch on the tool about $\frac{1}{8}$ in. thick conforming to the concave surface of the mirror. Keep the mirror in motion the whole time until the pitch cools sufficiently to retain its own shape, then slide off the mirror and let the tool cool down to room temperature. It is as well never to let the surface of the pitch lap be exposed to any possible falling dust, so whenever the

mirror is removed for any length of time place a sheet of paper over but not touching the lap.

The next step is to cut V-shaped grooves on the surface of the pitch as shown in fig. 15. These grooves assist in retaining the rouge and water mixture between the surfaces, and also, by dividing the lap into facets, determine to a large

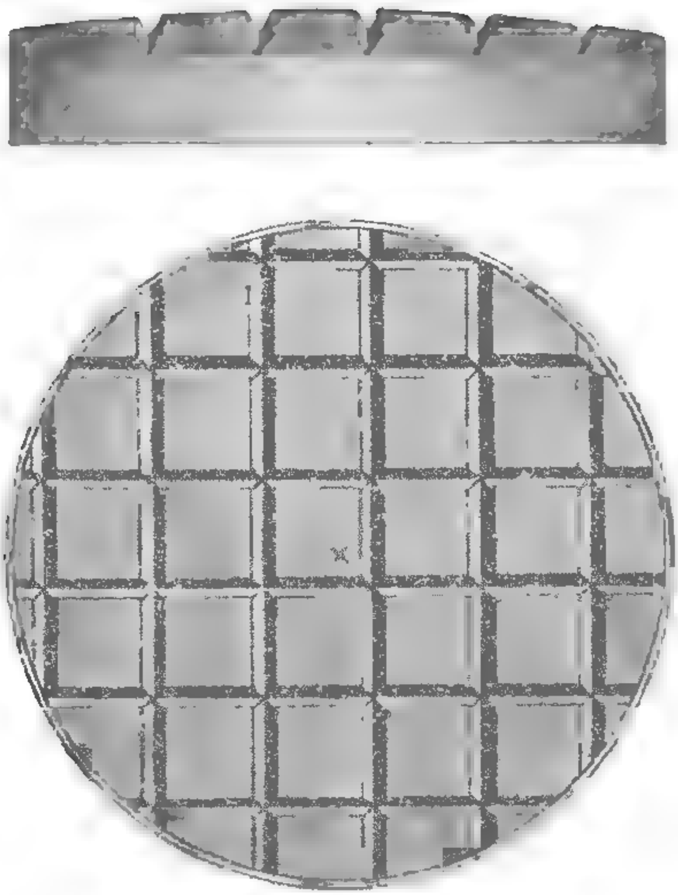


Fig. 15.—Pitch lap for polishing

extent during the process of figuring, the shape of the final surface. Cutting is most conveniently carried out by laying a strip of flexible steel or brass as a guide across the face of the lap, and cutting down to the glass at an angle with a sharp knife or razor. The distance between the grooves is not important, and about 1 in. apart will serve for our 6-in. diameter mirror, but care must be taken not to make them symmetrical in relation to the circumference or centre of the lap. If the centre facet is made directly in the centre it will be found that the

mirror will be polished in zones or rings, so first of all mark off the centre of the lap and then work outwards in cutting the grooves so that the centre of the lap is positioned near to a corner of the centre facet.

When the grooves have been cut, remount the lap on the pedestal, place a liberal quantity of rouge and water over the surfaces of the mirror and lap, and then proceed with the backwards and forwards motion as for grinding, using about two-thirds to half stroke. The lap may have altered its shape slightly whilst you have been cutting the grooves, so that it does not make perfect contact with the surface of the mirror, but it will soon bed down as the polishing progresses. The mirror will slide fairly smoothly over the surface of the lap, and it may be thought, after the feel experienced during grinding, that no action is taking place, but even after ten minutes or quarter of an hour if the mirror is removed and cleaned off it will be seen that the centre is beginning to take on a polish. This, incidentally, is a good guide as to the state of the pitch lap, because if all is going well the mirror should start to polish at the centre and gradually work outwards, but if the reverse is the case it shows that the lap is not in perfect contact with the mirror. If this should be the case, leave the mirror on the lap for an hour or so to bed itself down, making sure that it is supported so as not to slip off. There should of course be plenty of rouge and water on the lap if this is done, and placing a weight on the back of the mirror will shorten the time of standing.

Polishing will take anything from five to ten hours, depending upon the efficiency with which the fine grinding was carried out, so from now on it is all a question of patience and elbow-grease. Looking at the pitch lap through the mirror whilst polishing it will be seen that the rouge and water mixture is frothing up in the grooves, and that the surfaces of the facets are covered with a layer of rouge which, when dry, should present a matt appearance. The addition of rouge and water from time to time will be found necessary as the mixture gets worked out along the grooves.

Although our whole object at this stage is to obtain a

polished surface, and we could carry on with reasonable confidence until this had been obtained, it is as well, as soon as the surface has assumed a fair polish, to start testing by the method about to be described, so that there will be the minimum of work to be performed when we come to figure the surface to a paraboloid, and also to get experience of the method used.

CHAPTER V

Testing

The following method of testing the surface of a mirror was devised by Foucault in 1859, and is known as the Foucault Test. Prior to the discovery of this method, mirrors were figured by the principle of trial and error, and much labour and time was spent in arriving at the required paraboloidal surface.

Fig. 16 shows the apparatus used, which comprises a suitable source of light and a knife-edge. The source of light must be of pin-hole size, and is made by piercing a sheet of tin or aluminium foil with a needle and glueing it to the glass of an electric torch. The knife-edge can be of any thin sheet metal, and a safety-razor blade is ideal for our purpose. It should be mounted on a stand as shown, and this should be provided with a straight-edge along one of its sides for use when making the final tests after the mirror has been figured to a paraboloid. In addition to these two items some form of jig for holding the mirror during testing will be found to be a great time saver in setting up the mirror for testing.

The optical layout of the test is shown in fig. 17. The pin-hole light is placed at the radius of curvature of the mirror (96 in. in the case of our 6-in. mirror of *f*/8), and as previously explained the light will be reflected back to the same point. To enable visual examination of the point of focus, the light is moved a few inches to one side, which also has the effect of moving the focal point an equal distance in the opposite direction, so that if the light is moved 3 in. to the right the distance between the pin-hole and the focal point will be 6 in. The distance through which the light (*b*) is moved to one side should be just sufficient to enable the eye (*c*) to be placed behind the knife-edge (*a*). A, fig. 17, shows the set-up,

with the knife-edge inside the point of focus. In this position, if the knife-edge is travelled into the cone of light reflected from the mirror the image of the knife-edge will appear to travel across the face of the mirror in the same direction.

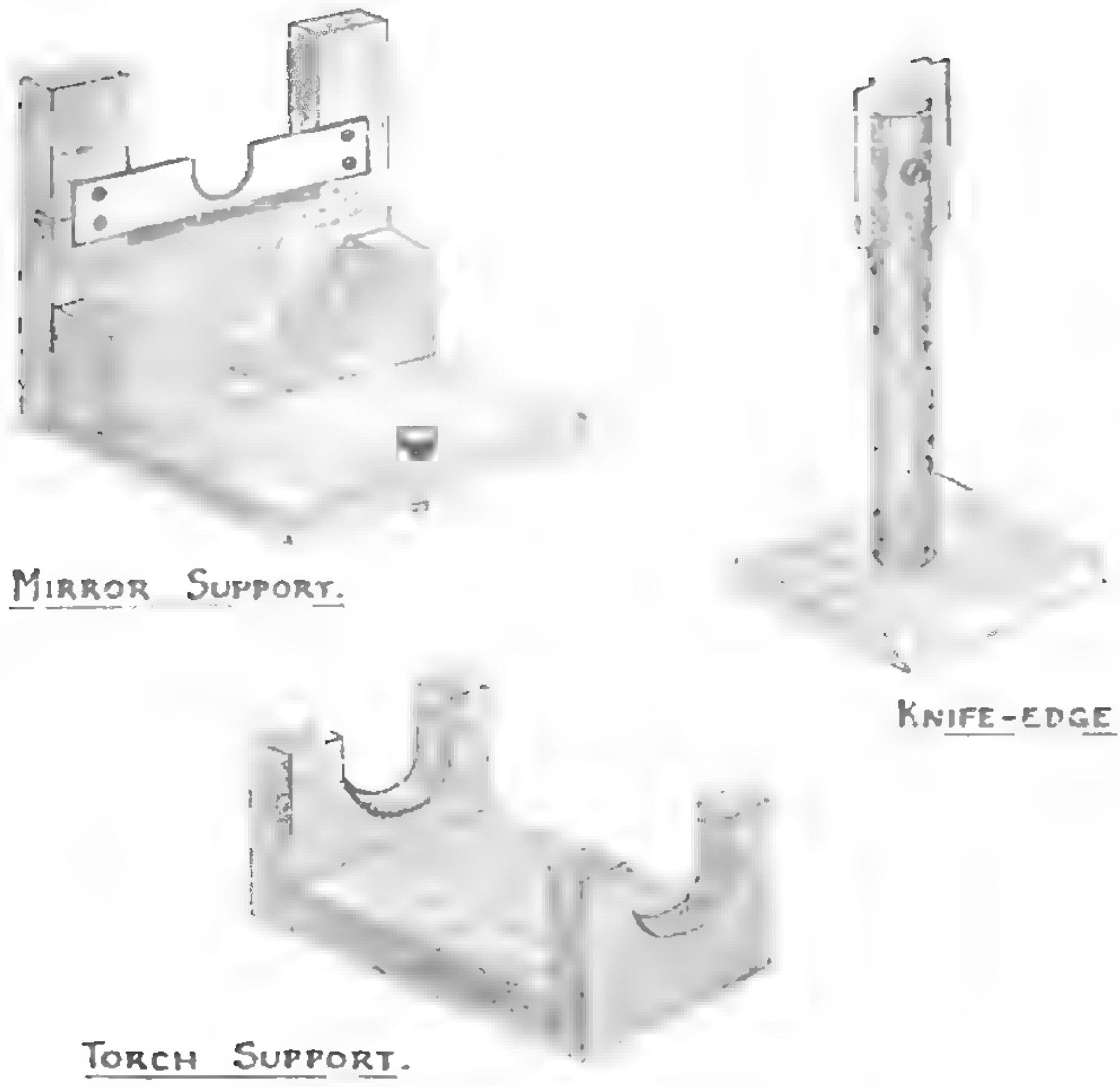


Fig 16.—Apparatus for Foucault test

In B, where the knife-edge is outside the point of focus, its introduction into the cone of light results in the image of the knife-edge appearing to travel in the opposite direction. If, however, the knife-edge intersects the cone of light at the focal point, the sharp outline of the knife-edge will not be seen, and the mirror will appear to darken evenly over its whole surface as the knife-edge is introduced. By this means we can determine the exact radius of curvature of our mirror

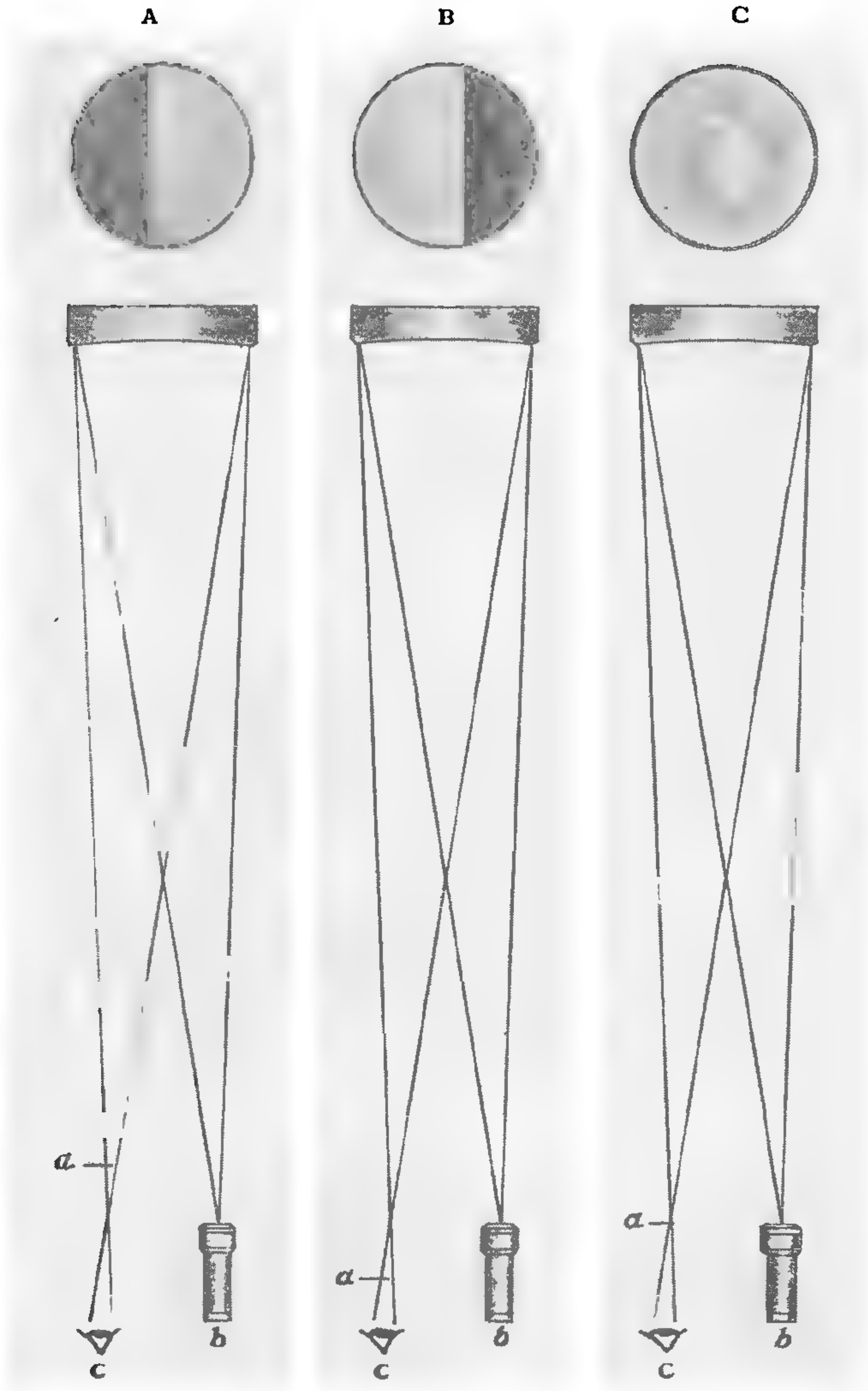


Fig. 17.—Testing for radius of curvature

by measuring the distance from the face of the mirror to the knife-edge. Half this distance will give us the focal length of the mirror.

In addition to being able to find the radius of curvature by the above method, we can also see the shape of our polished surface. It was mentioned above that when the knife-edge is inserted into the reflected cone of light at the focal point, the mirror will appear to darken evenly over its whole surface, but this is only true if the surface is a spheroid. If the knife-edge is made to cut the cone of light exactly in half, the surface of the mirror will appear covered with varying depths of light and shade according to the nature of the surface. The test made after the first spell of polishing will show the centre of the mirror to be much deeper than the edge, due to the fact that as the polishing starts in the centre of the mirror more glass has been polished away from this part than the outer edge. As the polishing proceeds, the various hollows, hills, rings, &c., which may form on the surface for one reason or another, can be clearly seen by means of the Foucault test. It should be pointed out at this stage that the apparent surface seen with the knife-edge test is highly magnified. To demonstrate this, hold the base of the clenched fist against the surface of the mirror for about half a minute, and then view the mirror from the knife-edge. The heat of the hand will have expanded the glass where it was in contact, and this area will be seen as an apparent large lump on the surface of the mirror. Assuming the glass to have been heated 10° C. through the whole of its thickness (and this is a gross over-estimate), the raised portion would only be ·00009 in. above the rest of the mirror, so some idea may be gained from this as to the delicacy of the test. It also demonstrates the need for fixing a handle to the back of the mirror whilst polishing and figuring, to prevent distortion of the figure, and the necessity for letting the mirror cool down after a spell of polishing if the true surface of the mirror is to be observed.

The foregoing description of the Foucault test shows that the accuracy with which the mirror is made depends upon the operator's ability to interpret correctly what he sees, and there

are circumstances in which this visual interpretation is very difficult. The image formed by a short focus paraboloid will not be the same as that made by one of long focus, and the difference lies in depth of shading so that it is only after much practice that the operator can say with certainty when he has parabolized his mirror.

Another method of testing, known as the Ronchi test, will no doubt have more appeal to the amateur inasmuch as he can see on the mirror dark bands which conform to the shape of the mirror. If the mirror is a spheroid, the surface will be covered with straight lines; if it is a hyperboloid the lines will show as a hyperbolic curve, and if it is a paraboloid the lines will exhibit a parabolic curve (fig. 18). The existence of a "turned edge" is also more clearly seen with this test than with the Foucault test.

In the main, the layout of the Ronchi test is the same as the Foucault test, and fig. 19 shows the essential differences. In place of the pin-hole source of light we have a slit, and the knife-edge is replaced by a wire grating having about one hundred lines to the inch. The slit can be made in a similar manner to the pin-hole by drawing a sharp knife or razor over the tinfoil or aluminium foil, and should be as narrow as it is possible to make it. Fig. 20 shows a method of making a wire grating, but it may be mentioned here that a piece of printers half-tone screen, or even gauze of fine mesh, can be used with success. The writer has a preference for the wire grating on account of the sharp outlines which it gives, and also by extending the grating it is possible to do away with the slit, as in fig. 19. The use of the extended grating is confined to visual work only, and if it is desired to photograph the effects seen with the Ronchi test a slit must be used.

If the grating is placed inside the focal point, the effect of bringing the grating closer to the point of focus is to observe the bands spreading out over the face of the mirror as though being increasingly magnified, until the point of focus is reached, when the appearance of the mirror is the same as that with the knife-edge at the point of focus. As the grating is brought farther back from the focal point, the lines appear

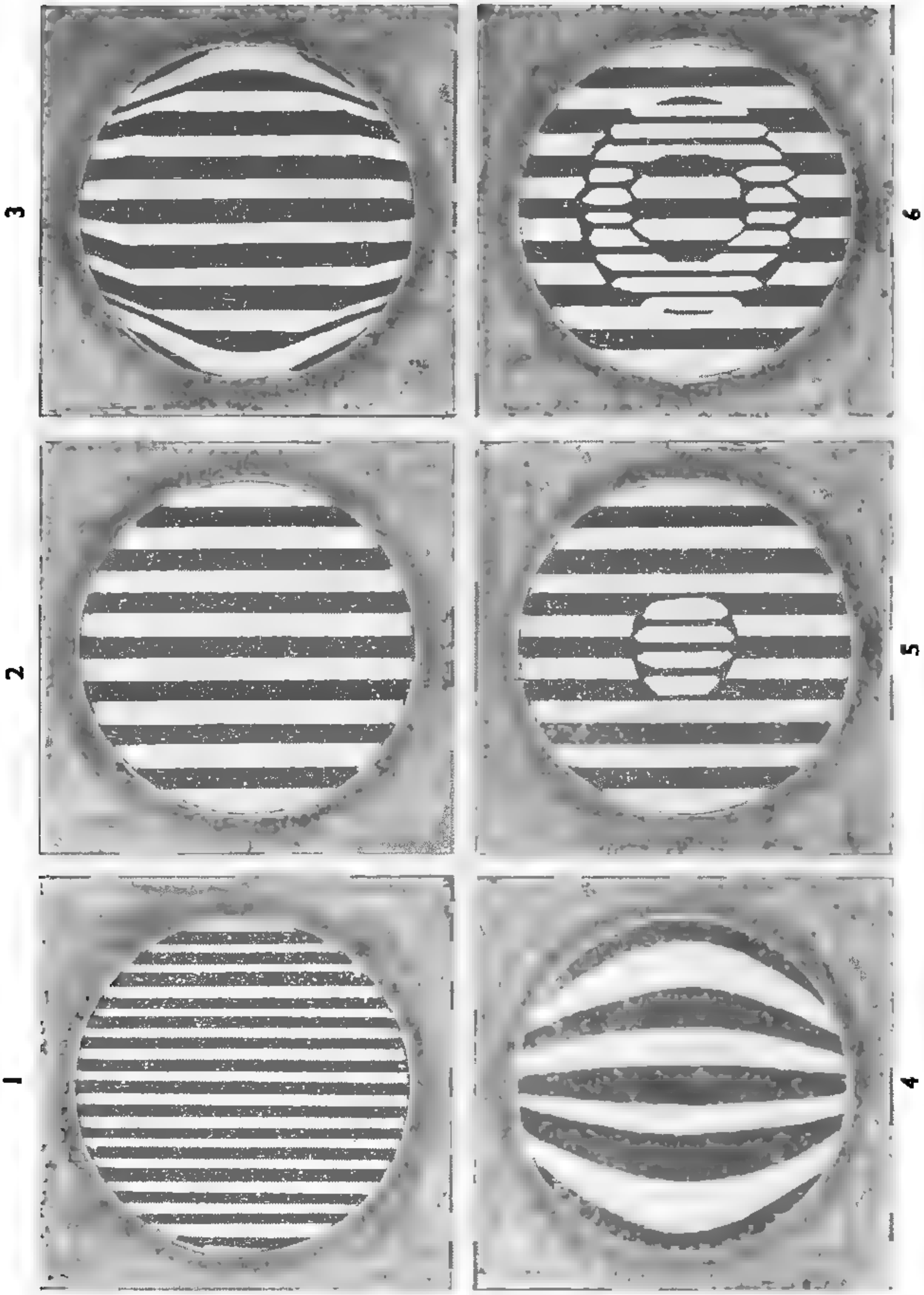
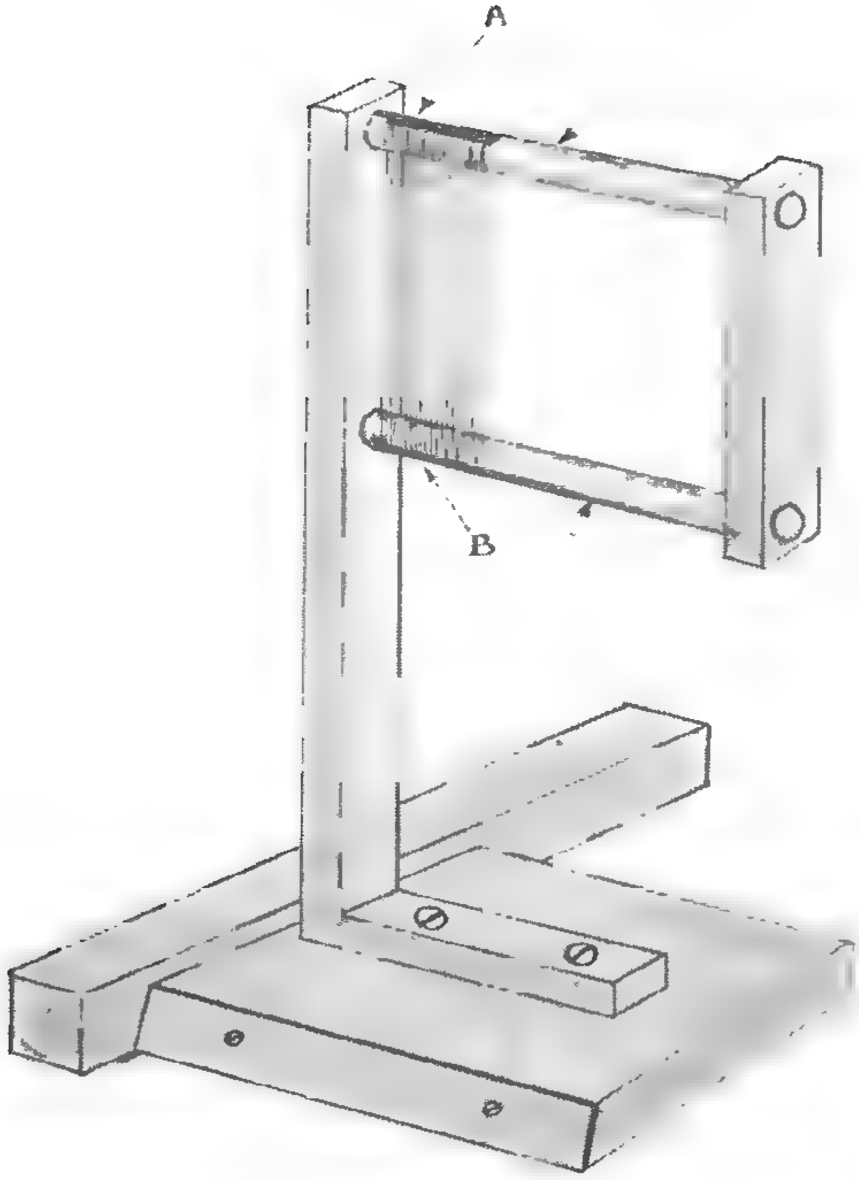


Fig. 18.—Ronchi test

1. Spheroid, with grating inside focus.
2. As 1, but with grating nearer to focal point.
3 Spheroid, with turned edge.
4. Paraboloid.
5. Spheroid, with raised centre.
6. Spheroid, with raised ring.

Fig. 19.—Ronchi test

again, getting closer and closer together as the grating is moved back. To avoid confusion, all tests carried out by this method should be made inside the focal point. The question of quantitative measurement by either the Foucault or Ronchi tests will be discussed later when we have completed the preliminary figuring.



Brass rods threaded 100 T.P.I. and wound with 40 g copper wire. Soldered at A and B and one side cut away

Fig. 20.—Grating for Ronchi test

CHAPTER VI

Figuring

Examination of the outer edge of the mirror with a magnifying glass will tell us when the mirror has been sufficiently polished. If the work has been properly carried out the surface should be free from pits made by the carborundum, and if any exist they can be clearly seen by holding the glass at an angle and viewing the reflection of say the filament of a lamp. It is quite likely that your first attempt will show quite a few of these pits, but provided they are spaced well apart from one another they will not seriously affect the efficiency of the mirror, and if the surface appears well polished to the naked eye without any trace of haziness, it will be quite in order to proceed with the next stage of figuring the mirror to a paraboloid.

The first step is to figure the surface to a spheroid, and then to deepen the centre portion so that it takes on the surface of a paraboloid. When you have decided that the mirror is polished to your satisfaction, let it stand on the testing bench for half an hour so that it is at a constant temperature, and then test with the knife-edge or grating. The chances are about a hundred to one against it being a perfect spheroid, but whatever shape it is, get a sheet of paper and make a sketch of what you can see, either in plan or section as in fig. 21. The business of keeping a record of how the work is progressing may seem a waste of time, but you will find in the long run that it actually saves time, particularly if you have a mirror covered with bumps and hollows, and if you intend making more than one mirror the information at your disposal will prove invaluable. Don't work on the assumption that you are only going to make one mirror, because you may find, as hundreds of other people have found (the writer included),

that mirror-making has a fatal fascination, and once bitten by the mirror-making bug you are liable to break out into ever-increasing apertures.

The most common defects which are found when the mirror has been polished are: (1) a hill or depression in the centre; (2) a raised or sunken ring at any point along the diameter;

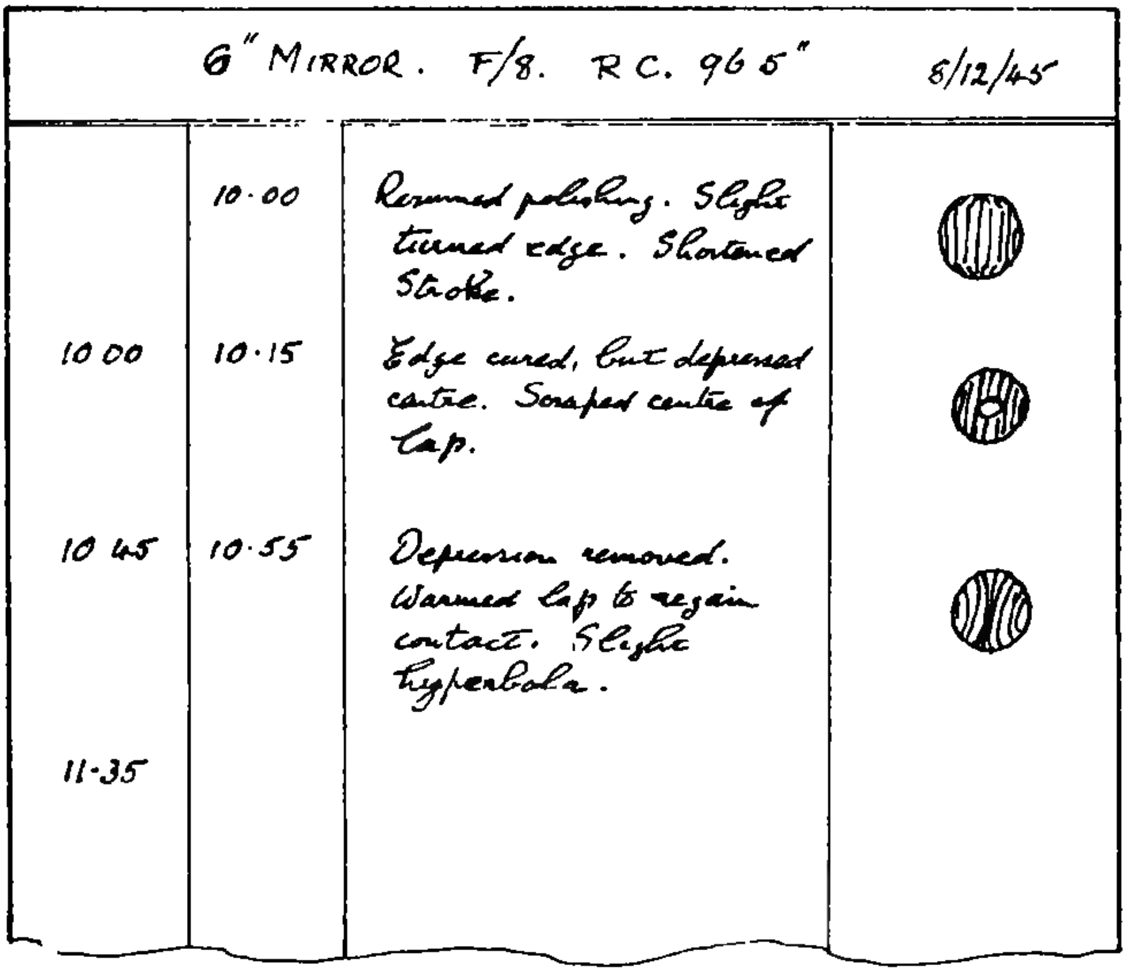


Fig. 21.—Polishing record

(3) a turned-down, or turned-up, edge; (4) a combination of any of these three. We will now consider the methods used to get rid of these defects, which are mainly caused by an imperfect lap or incorrect strokes.

(1) *A hill in the centre.* This has probably been caused by the lap not making good contact in the centre, and can be quickly removed by adopting side stroke as shown in fig. 22, where the centre of the mirror, instead of travelling along the diameter of the lap, is moved to a point at or close to the edge of the lap. The straight backward and forward stroke

should be changed to a circular or elliptical motion when using the side stroke, and frequent tests should be made to observe progress as the action is fairly rapid, and if overdone you may be left with a hollow in place of the hill.

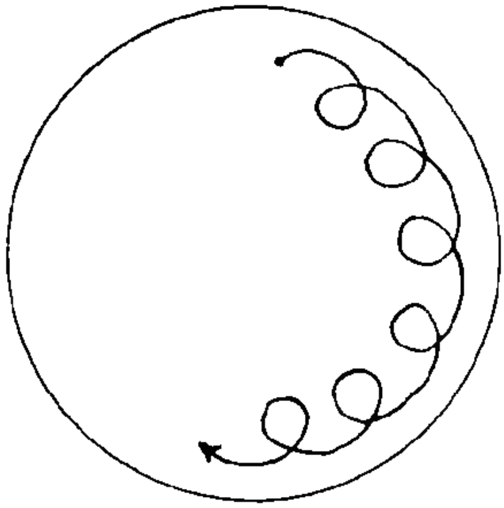


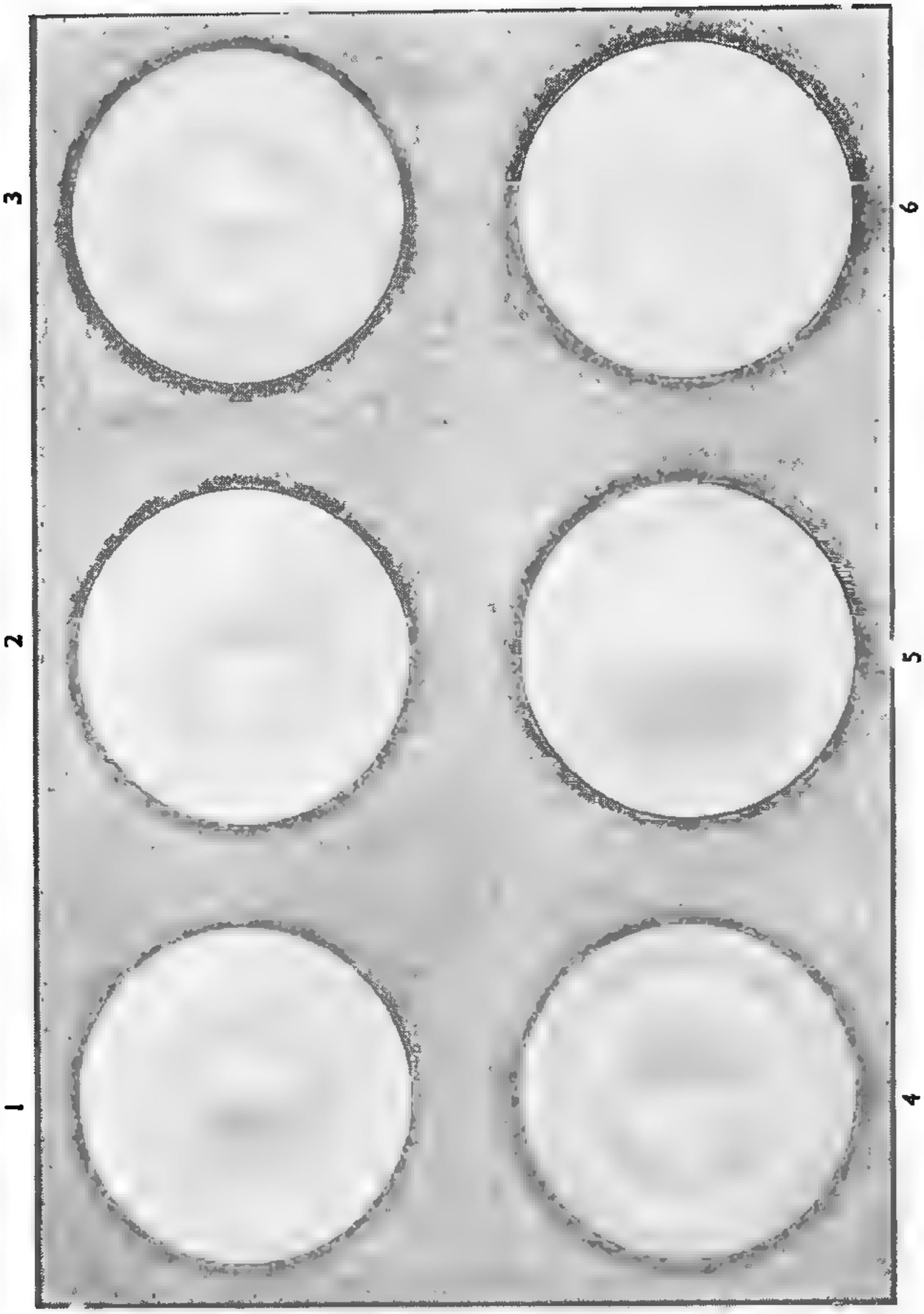
Fig. 22.—Side stroke. Showing path of centre ot mirror over tool

(2) *A hollow in the centre.* This will entail a bit more work owing to the larger area of glass which has to be removed It is obvious that if a hill was formed in the centre by bad contact, then if we deliberately make an area of bad contact in the centre of the tool approximately the same as the hollow, that portion of the mirror over the area of incomplete contact will not receive the same amount of polishing action as the remainder, and the rest of the mirror will be worn down to the base of the hollow, thus evening up our curve. Once again frequent tests must be made so as not to overshoot the mark.

It is as well to remember that hollows may be caused by heat from the hands expanding the glass unevenly, thus forming raised portions which are polished off, and when the mirror cools down these portions contract to form depressions. Provided you work in short spells of not more than five minutes, you should not experience any trouble in this respect, but if you come up against a hollow which persists in being a hollow, and is reluctant to leave the mirror, try insulating the back of the mirror and handle with felt or corrugated cardboard cut to shape.

To get rid of our hollow in the centre, all we have to do is to scrape off an area from the centre of the tool approximately equal in size to that of the hollow. The scraping should be done very lightly with a razor blade, just sufficient to remove the rouge and expose the black pitch. In this connexion, it should be pointed out that altering the surface of the lap is not to be recommended if it is possible to use some other method, such as alteration of stroke, as there is always the possibility that too much will be taken off, with the result that, if you continue polishing after removing the hollow, you are bound to get a hill in its place. If you have to resort to altering the lap, make sure that when you have removed the hollow the lap is brought back into complete contact. This is best done by placing the lap in warm water to soften it slightly, and then remoulding it with the mirror, and allowing the whole to cool to room temperature before resuming polishing.

(3) *A turned-down edge.* This is a very bad fault, not only on account of the difficulty of correcting it, but also if it is not properly cured it will result in bad definition in the finished mirror. It is an almost inevitable result of using too long a stroke, or a soft lap. Try using very short strokes, and if this does not effect a cure it will be necessary to make another and harder lap. In extreme cases where the turned edge exists for some distance along the diameter, it may be quicker in the long run to make a fresh lap about ½ in. to 1 in. less in diameter than the mirror. This can be made from a hardwood base turned to the shape of the tool, on which the pitch is poured and the lap made as previously described. A turned-down edge is most readily recognized by substituting an eyepiece of say 1 in. focal length, for the knife-edge, when a sharply defined image of the pin-hole will be seen. If the eyepiece is now moved forward to inside focus, the disk formed by the pin-hole should gradually expand and the outer edge should remain fairly sharp. If, when about a quarter of an inch inside focus, the pin-hole appears fuzzy or hairy, then there is no doubt about the edge of the mirror being turned down.



Foucault test

1. Hollow centre.
2. Raised centre.
3. Hollow centre and hollow ring.
4. Raised centre and raised ring.
5. Paraboloid.
6. Raised ring.

(4) *A turned-up edge.* It is very unlikely that you will come up against this defect, and it can only be caused by your tool or lap being very much smaller in diameter than the mirror. The cure is obvious Lengthen the stroke. It can also be cured by inverting the lap and mirror, but use this method with caution.

(5) *A depressed ring.* Rings on a mirror are probably caused by the lap being too symmetrical, or bad contact may have the same effect. A depressed ring can be dealt with by shaving one or two facets in the path of the ring, so that less polishing action takes place along the area of the ring. As mentioned before, the scraping of the lap should be very slight.

(6) *A raised ring.* This is best treated by using side stroke with an elliptical motion, so that the ring is brought to the edge of the lap, but bear in mind that too much of this side stroke will cause a turned-down edge.

If you have a combination of any of the above defects, first of all decide how you will eliminate one of them and then reason out if this will affect any of the others. By close reasoning and plenty of practice you will soon learn how to lick a mirror into shape.

CHAPTER VII

Parabolizing

Having got rid of all the hollows and bumps and ascertained by the Foucault or Ronchi tests that we have at last made our surface into a spheroid, we next proceed to deepen the

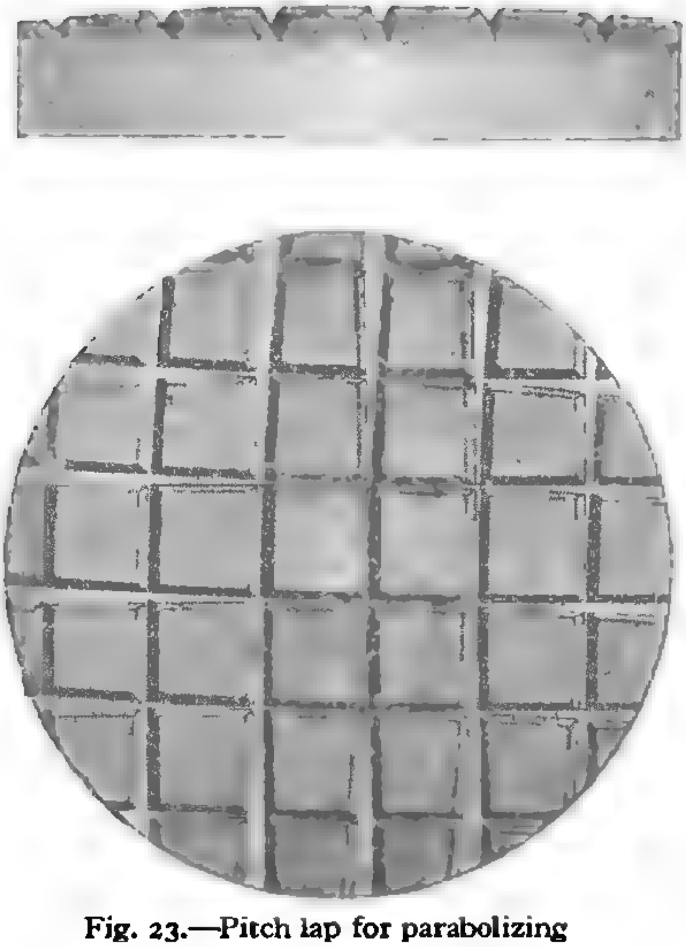


Fig. 23.—Pitch lap for parabolizing

curve to a paraboloid. There are several ways in which this can be done, and perhaps the easiest for the beginner is by means of the graduated lap. Fig. 23 shows how the lap is cut, so that the area of contact is greatest in the centre and gradually diminishes towards the circumference. If it is carefully made and pains taken to ensure perfect contact, a series

of short strokes on a lap of this description should give us the desired curve, but owing to the " cussed " nature of pitch it is never possible to forecast with any degree of accuracy how a pitch lap will behave. Even after some years of experience one comes up against a lap which seems to have a vicious nature and will not respond to the bidding of the operator. However, the graduated lap is the one which should theoretically give us a paraboloid, so try it out and see how you get on. By using some of the tricks you have learned in making the spheroid, you should be able to coax the surface to a paraboloid by this method.

The method which seems the most obvious is to lengthen the stroke, as by this means the centre will be deepened more than the edge, but although this method can be used in expert hands there is always the danger of developing a turned-down edge. Similarly, side stroke could be used, but here again there is the bogey of the turned-down edge. A combination of side stroke with a circular or elliptical motion, used with varying distances along the radius of the lap, can be used with very good effect, but requires some experience.

Another method is to use a lap of smaller diameter than the mirror, about half size, but once again this should only be tried after considerable experience has been gained, as some very undesirable results can be obtained in inexperienced hands.

Whatever method is employed, short spells of polishing are the watchword, as even half a minute can make a pronounced difference to the curve, and at least half an hour should be allowed before testing to ensure that the mirror is of even temperature. Mark the word *even*. A mirror at 20° C. will give on test the same figure as it would at 30° C., provided that the degree of temperature exists throughout the whole of the mirror. It is only due to the increased temperature on the face of the mirror, caused by friction in polishing, that makes it necessary to leave the mirror to cool down, as this increased temperature on the *surface only* causes the surface to expand whilst the rest of the mirror remains in a normal state, and consequently the figure becomes distorted. Always

remember that the mirror as taken off the lap has an entirely different figure when it has been allowed to regain an even temperature, and on this account patience is essential to accurate work. It is not easy to wait for half an hour when you are itching to get the mirror completed, but during these spells of waiting take an occasional look at the mirror, and see for yourself the vast change which takes place as the glass is cooling. The time can also be profitably filled in by making notes of what you have done, with appropriate diagrams and observations on the results produced. And remember to cover over your lap when you remove the mirror so that no damage can be done by dust.

When the surface has finally been figured to a paraboloid, a quantitative test should be made to ascertain the actual state of your paraboloidal curve.

As has been explained, we have deepened our mirror in the centre so that the radius of curvature will be shorter at this point than at the edge. The difference between these two radii in the case of a parabola is given by the formula r^2/R, where r is the radius of the zone being tested, and R is the radius of curvature of the mirror. In the case of our 6-in. mirror, with r equal to 3 in. and R equal to 96 in., the difference in the radii will be 0·09375 in. If, therefore, we place a mask over the mirror so that only a small portion of the centre is visible, and then ascertain the radius of curvature, and then substitute another mask which will allow only the outer edge of the mirror to be visible and find the radius of curvature of this portion, we shall be able to determine whether the curve is parabolic.

Fig. 24 shows a suitable mask for carrying out this test. This is placed in front of the mirror, and the knife-edge base is placed on a piece of drawing paper or card, and the radius of curvature of the centre zone is found and recorded by drawing a fine pencil line on the card by means of the straight-edge. The radius of curvature of the outer zone is then determined and recorded in the same way. Owing to the difficulty of judging exactly when the radius of curvature has been found for each zone, it will be necessary to make several tests

and to take the average as representing the true point. The distance between the two marks made on the paper or card should of course be equal to r^2/R, or 0·09375 in. in the case of our 6-in. mirror, but it is possible to allow a margin of plus or minus 45 per cent (in the case of a 6-in. diameter mirror of $f/8$).

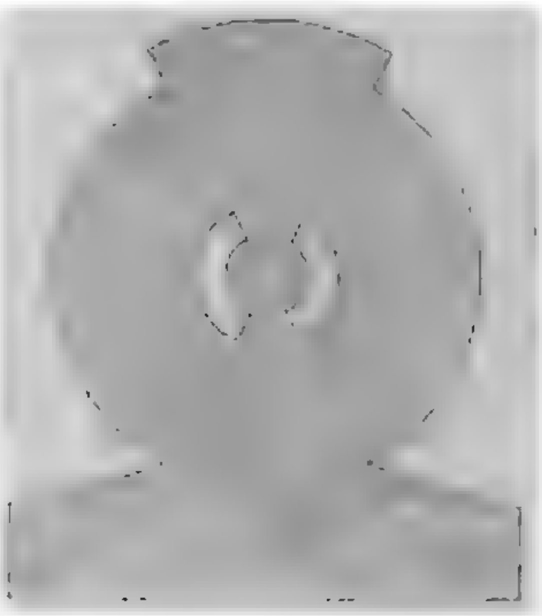


Fig. 24 —Mask for zonal testing

Note. The formula r^2/R is only applicable if the knife-edge is moved independently of the source of light, and if the two are mounted on the same base, then the formula $r^2/2R$ must be used.

A better picture of the actual curve of the mirror will be obtained if several zones are tested for radius of curvature and the results plotted as a graph against the theoretical graph for a perfect mirror, and the graphs for 45 per cent under and over, as in fig. 25.

If the Ronchi test is used, the degree of overall correction is obtained by adjusting the grating, so that the two bands or lines at the centre are, say, 1 in. apart as seen on the mirror, and then marking the paper or card as described above. The grating is then moved back so that the lines at the edge of the mirror are 1 in. apart, and the paper again marked. The distance between the two markings should be equal to r^2/R.

Intermediate zones can of course be measured in the same way, but the curve of the lines will give a true indication of the curve of the mirror, so this is not really necessary.

That completes the description of how the mirror is made, but before going on to describe how the surface is silvered,

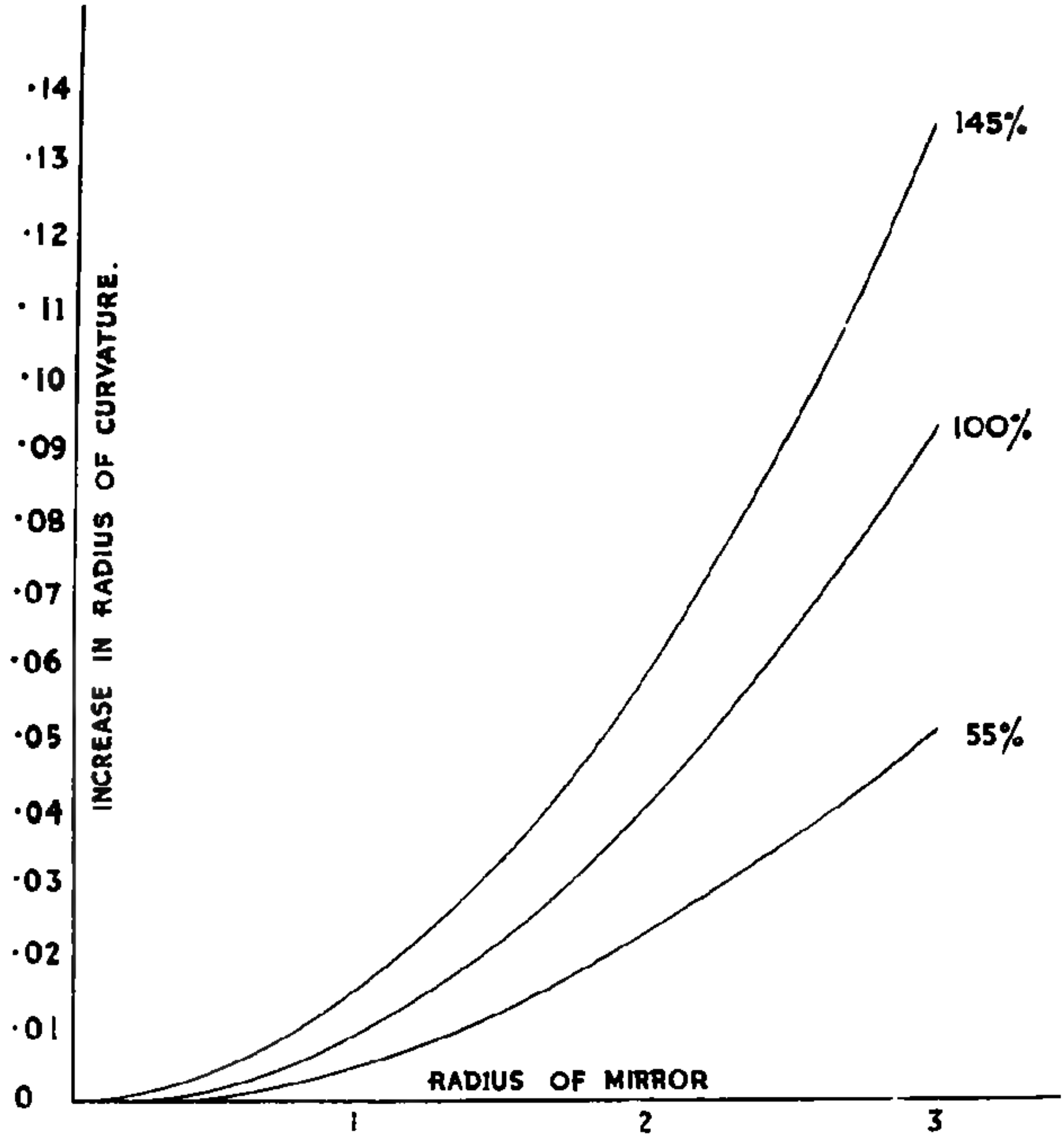


Fig 25.—Parabolic curve for 6-in. mirror. *F* 8

I would like to run over the main points that should always be kept in mind. First of all, don't start off by thinking, " I'm only an amateur so the final result can't be perfect ". If you adhere closely to the instructions given there is no reason why your mirror, even if not perfect, should not be at least equal in performance to the early attempts of those amateurs who started in the same way as yourself and are now

among the leading authorities on the optical working of glass. Always aim at perfection—the words " near enough " are not in the vocabulary of the mirror-maker.

Don't go at your work like a bull in a china shop. In grinding and polishing, the number of strokes per minute should not be more than sixty, and if you exceed this to any great extent you may find your working time doubled or, in the initial hollowing out, that your mirror refuses to become concave. Pay particular attention to cleanliness, not only in the polishing and figuring, but through every stage of production. When you resume work on polishing or figuring after an interval, make sure that you have perfect contact. Keep your eye open for thermal effects. And get into the habit of keeping a record of your work—it pays good dividends.

CHAPTER VIII

Silvering

If you have some knowledge of chemistry and experience in practical work, the job of silvering the mirror should not present any difficulty, but it is an exacting business, and if you feel that it is beyond your powers it will be best to leave this part of the work to the professional. Many of the scientific instrument-makers undertake this work, and if you hand over the mirror to them for silvering you will have the satisfaction of knowing that your mirror has received a coat worthy of all the care and trouble you have taken over it. If you consider your finished mirror is worth it, have it aluminium coated. It is rather more expensive than silvering, but the aluminium coat has a longer life on account of its greater resistance to oxidation. For those who want to tackle the job, and for those who will try anything once, the following instructions are given. After all, if your efforts prove to be a failure it is a simple matter to clean off the coat of silver and no harm will be done to the mirror, and then you can either have another try or pack it off to the professional. I would strongly advise against having the mirror silvered by a maker of ordinary looking-glass mirrors, but if you should entrust this work to one, stand by the side of him whilst the work is being carried out and impress upon him the fact that it is the front surface you want silvered, and that you want to reflect light direct from the silver and not through the glass. If you don't take these precautions you may find that you have a perfect reflecting surface when seen from the back of the mirror, but that the front surface is not so good. He may even put a coat of backing-varnish on it.

There are one or two methods by which a coat of silver can be deposited on glass, but I shall only describe the one known

as Brashear's process, which, although not necessarily the easiest to carry out, is the one which in the opinion of the writer will give the best results.

The chemicals required are:

Silver nitrate.
Distilled water.
Caustic potash.
Ammonia (sp. gr. 0·880).
Nitric acid (sp. gr. 1·420).
Sugar (large crystal).
Alcohol, or isopropyl alcohol.

First of all you must get your mirror chemically clean. Wash the mirror well with soap and water, and after draining off the surplus water, pour on a little concentrated nitric acid and rub this well over the whole surface with a pad of cotton-wool. Rinse well under the tap, and repeat the cleaning with nitric acid. Then rinse again under the tap and finish off with distilled water. If the cleaning has been properly carried out the mirror will remain covered with a thin film of water if it is held on edge to drain for a few seconds. If patches of the glass are exposed when this is being done, it shows that there are still traces of grease which will have to be removed with the nitric acid. When you are satisfied that the mirror is clean, immerse it face upwards in a dish of distilled water, which should be slightly larger than the mirror, and the sides of which should extend about 2 in. above the surface of the mirror. Leave the mirror in the dish of distilled water so that it is covered with about ¼ in. of water, and then proceed to make up the *reducing solution*, as follows:

Sugar	75 gm.
Nitric acid	3 c.c.
Alcohol	150 c.c.
Water, distilled	1000 c.c.

Put the distilled water in a flask suitable for boiling, add the sugar and nitric acid and simmer (not boil) for ten minutes. Allow it to cool down and then add the alcohol. This reducing

solution should be stored in a stoppered bottle, and will keep indefinitely.

Two more solutions are then prepared:

(1)	Silver nitrate	.. .. ..	25 gm.
	Distilled water	.. .. ..	250 c.c.
(2)	Caustic potash	.. .. ..	15 gm.
	Distilled water	.. .. ..	150 c.c.

The silver nitrate solution should be stored in a dark glass bottle as it will deteriorate if exposed to light, and the bottle used for the caustic potash should be provided with a rubber stopper.

The amount of silver nitrate required to give a good coat on a mirror can be calculated by dividing the area of the mirror in inches by four, and expressing the result in grammes.

Area of mirror in inches/4 = grammes of silver nitrate. For our 6-in. diameter mirror we shall therefore require 28/4 or 7 gm. of silver nitrate. As each c.c. of the silver nitrate solution prepared as above contains 0·1 gm. of silver nitrate, we shall require 70 c.c.

Place the 70 c.c. of silver nitrate solution in a glass jar or beaker, and start adding ammonia, *drop by drop and stirring vigorously*, when it will be found that the solution assumes a dark-brown colour, which gradually gets lighter and lighter as the ammonia is added. Continue adding ammonia very slowly until the solution is just slightly milky. If you overstep the mark and the solution becomes clear, add a few drops of the silver nitrate solution until the milkiness is regained. Then add 35 c.c. of the caustic potash solution, when the mixture will become a dark-brown colour. Ammonia is then added drop by drop with constant stirring until the solution is of a light straw colour, and then in order to be certain that the silver is in excess, a few drops of the silver nitrate solution are added. At this point the solution will be of a muddy appearance which cannot be dispelled by stirring, and it should then be filtered through cotton-wool ready for use.

Note. Silver nitrate solution to which ammonia has been added *should never be kept*, as there is the possibility of silver

fulminate forming, which is *highly explosive*. Also, the solution whilst being prepared should not exceed a temperature of 18° C., as this will tend to form silver fulminate. Make sure by means of a thermometer that your solution is between 15° and 18° C.

Pour out 50 c.c. of the reducing solution into a jar or beaker ready for use. The ammoniated silver solution and the reducing solution are then both poured into the dish containing the mirror covered with distilled water, and the silver will start to deposit immediately. The dish should be rocked from side to side to keep the solution in motion, taking care that the surface of the mirror is not exposed to the air for more than a second or so at a time. The time taken for a good film of silver to form will vary according to the temperature of the solution (which should not exceed 18° C.), and will take from two to ten minutes. Examine the surface of the mirror from time to time as you are rocking the dish, and as soon as a white bloom begins to form, stop the process by taking out the mirror and rinsing well under the tap. Finish off with distilled water, so that there will be no deposit when the mirror is dried off, and then stand the mirror on edge in a warm dry atmosphere. The silver film at this point is extremely delicate and care must be taken not to touch it with the hands.

Dilute the used solution well by pouring it into a bucket of water, and pour the lot down the drain. Clean up your dishes, &c., immediately, to prevent the possibility of silver fuminate forming.

When the mirror is thoroughly dry, clean off any white bloom which covers the silver, by rubbing very gently with a pad made from chamois leather and cotton-wool, and finish off by polishing with a little of the finest rouge. (Rouge which has been used for polishing and is found floating on top of the water is excellent for this purpose. It should be skimmed off and dried out in a wide-mouthed two-ounce bottle, which should be well protected from dust.) This operation of cleaning off and polishing the mirror must be carried out with the greatest care, and a very delicate touch, otherwise you may

lift off the silver. When completed, the film should be quite bright, and if you can see the filament of an electric lamp through the film at a distance of about two feet, the thickness will be about right.

When not in use, the mirror should be kept in a warm dry atmosphere, and a special container made as in fig. 40. If properly looked after, the silver will keep its polish for a period of six to twelve months, depending upon the local atmospheric conditions.

For the benefit of those who have not had any experience of carrying out work of this nature, I would add the following points:

1. Wear rubber gloves when doing the silvering, as the nitric acid is extremely corrosive, and the silver solution will also leave a dark black stain which can only "wear off". Similarly, wear old clothes.

2. For the sake of safety this work should be carried out in the open on a day when the temperature is that required by the process (15° to 18° C.), unless you have a room or workshop suitable. It is also advisable to wear goggles, just in case of accidents.

3. The success of silvering depends entirely upon the purity of the chemicals used, accuracy in measuring, and working at the correct temperature. Needless to say that the apparatus used should be spotlessly clean, and every step taken to avoid contamination. Some latitude is allowable in the quantities given, but they should be adhered to as closely as circumstances permit.

4. If your first attempt is not a success, dissolve off the silver with nitric acid and have another try.

CHAPTER IX

The Prism or Diagonal Flat, and the Eyepiece

Referring back to fig. 3, it will be seen that there are two more optical parts needed to complete the Newtonian reflector, these being the prism and the eyepiece. The object of the prism is of course to divert the rays of light from the mirror to a convenient point on the telescope tube, and it is obvious that a flat silvered piece of glass would serve the same purpose. Whatever method is adopted, it is essential that the diagonal surface should be *optically* flat. The prism is more costly

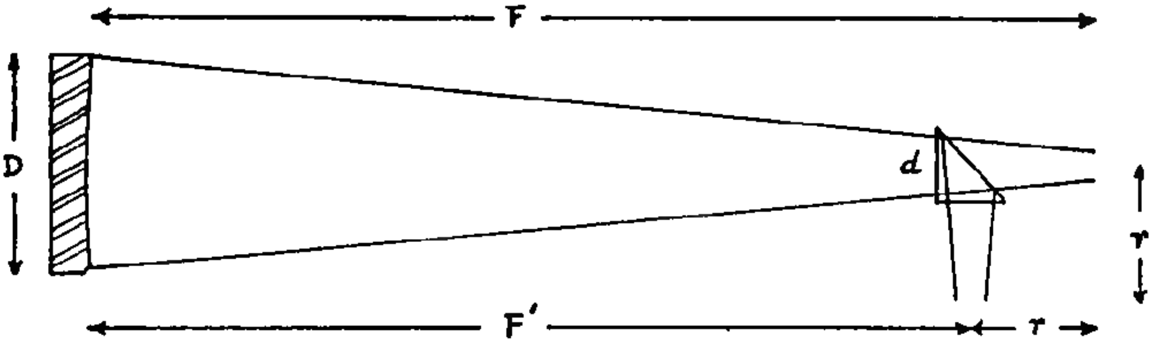


Fig. 26.—Size of prism or diagonal

than the flat, but has the advantage of reflecting more light, and has no silvered surface subject to deterioration and consequent periodical renewal. The optical flat has the advantage of being so shaped as to obstruct less light entering the telescope tube than would be the case if an equivalent prism were used. Assuming a prism of 1·25 in. square base, this would present an area of obstruction equal to 1·56 sq. in., whereas an optical flat of 1·25 in. minor axis would only present 1·23 sq. in. This more or less cancels out the better reflecting power of the prism, but still leaves us with the fact that the flat is subject to deterioration. It might be argued that as

the main mirror will have to be resilvered after a period, there will be no extra work or cost involved in resilvering the flat as this can be done at the same time as the mirror. From this it would seem that the only governing factor in the choice of the second reflecting surface is one of cost.

To find the size of the prism or diagonal required, the following formula should be used (see fig. 26):

$$d = \frac{rD + F'x}{F},$$

where

d = minor axis of flat, or length of the square face of prism,
r = distance from axis of telescope tube to field lens of eyepiece,
D = diameter of mirror,
F′ = focal length of mirror, less the distance r,
F = focal length of mirror,
x = diameter of field lens of eyepiece.

x may be taken for all practical purposes to be $\frac{7}{8}$ in. In our 6-in. diameter telescope, therefore, if we assume the tube to be 7 in. diameter, and the field lens of the eyepiece to be at a point $\frac{1}{2}$ in. outside the tube, we get the following value for d:

$$\frac{(4 \times 6) + (44 \times \frac{7}{8})}{48} = 1 \cdot 3 \text{ in.}$$

If we decide to make an optical flat we shall have to proceed as follows. First of all, the shape of the diagonal will have to be that of an ellipse as shown in fig. 27A, with a minor axis of 1·3 in. and a major axis of 1·85 in. (The length of the major axis is found by multiplying the minor axis by 1·42.) Imagine a solid bar of glass 1·3 in. diameter, cut through at an angle of 45° as in fig. 27C, and this will give you a good idea as to the shape required. Plate-glass, $\frac{1}{4}$ in. thick, will be required, and it may be possible to select a piece sufficiently flat for our purpose without having to resort to figuring the surface to the necessary degree of flatness. Cut out three pieces of plate-glass 2 in. long × $1\frac{1}{2}$ in. wide, and number them 1, 2 and 3. To test their degree of flatness the glasses

are thoroughly cleaned so as to be free from grease or dust, and two of them are pressed together, when it will be found that if reflected light from the surfaces in contact is viewed

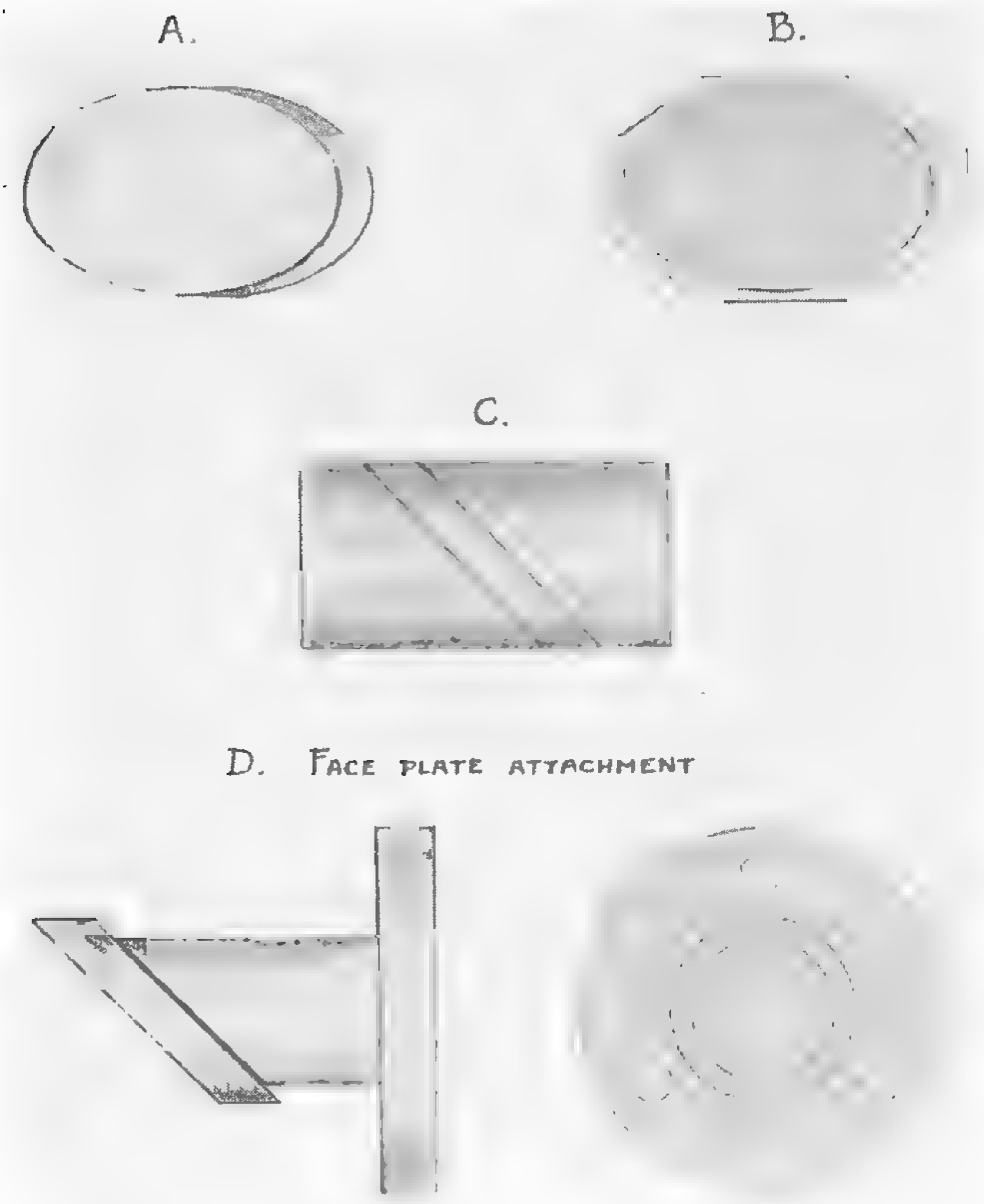
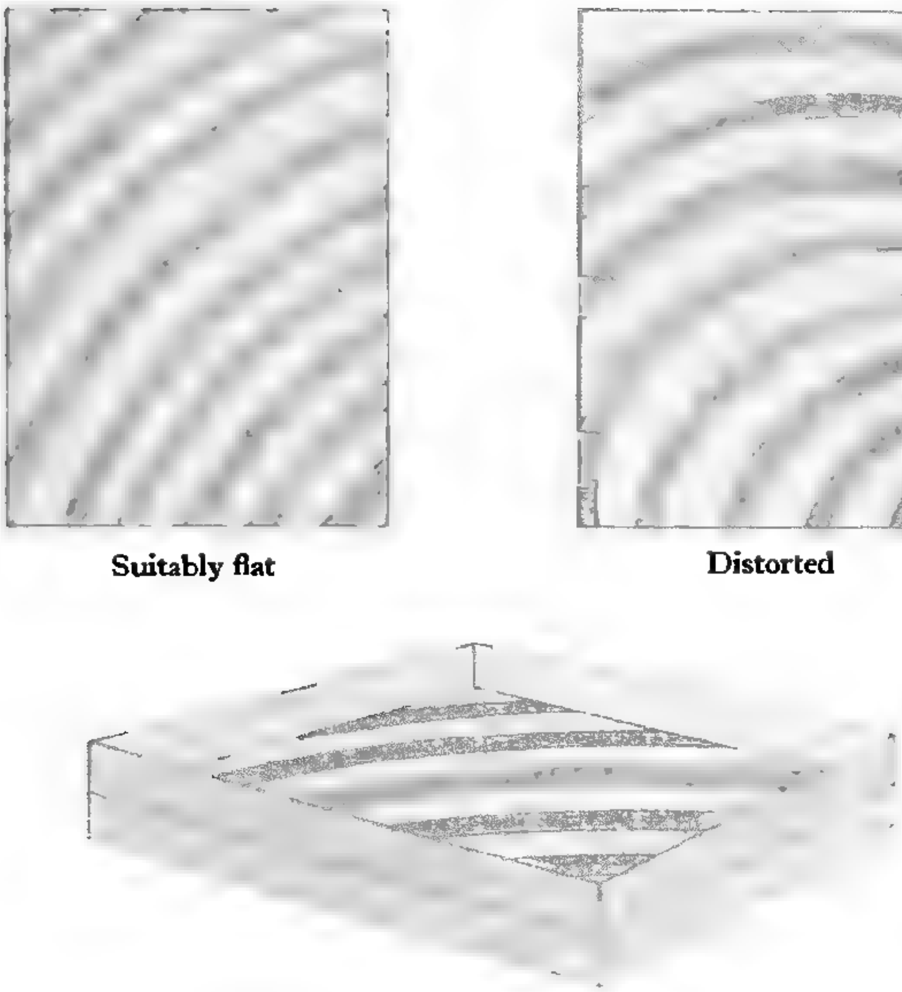


Fig 27.—The diagonal

at an angle, as in fig. 28, the surfaces will be covered with coloured bands of light. If the bands of light are circular, or semicircular in shape, it shows that the surfaces are concave or convex, and the glasses should be tried 1 on 2, 2 on 3,

and 3 on 1, until a pair is found where the bands of light are the nearest approach to straight lines, and one of the pair can then be used to make the diagonal. The above test is more easily observed if monochromatic light is used, such as is emitted by a sodium vapour lamp.



Suitably flat   Distorted

Fig. 28.—Testing for flatness

Having selected the piece of glass, it is roughly cut to shape by cutting off the corners as in fig. 27B. If an ellipse of the required size is cut out from gummed paper and stuck on to the glass, it can then be further rough cut to shape by nibbling away the periphery with a pair of pliers. Before grinding to shape it is advisable to cement on to each face a piece of ordinary window glass, as the acute angles formed at the ends of the major axis tend to chip away during the grinding. Pitch is used for cementing the glasses together

and for cementing the whole set-up on to the turning spindle (fig. 27D). A sheet of iron, brass or zinc about 3 in. wide is made into a part tube and used in the same manner as for grinding the edge of the mirror. No. 220 carborundum will be found best for grinding, and finish off with a finer grade. When the edge has been ground to shape, remove the diagonal from the spindle by a sharp blow with a wooden mallet, remove the protecting pieces of window glass in the same manner, and finish off the diagonal by making a slight bevel around the edges. The pitch used for cementing should not be scraped off, as this will tend to damage the surface, but it is easily removed by soaking in turpentine, when it can be wiped off with a soft rag.

The diagonal can of course be silvered at the same time as the mirror by placing it face upwards in the same dish.

The Eyepiece

Although it is well within the capabilities of the amateur to produce his own eyepieces, a lathe is an indispensable requirement to their production, and for that reason I will only give a brief description of the various types in use. For those who wish to go the whole hog, I would recommend their getting a copy of *Lens Work for Amateurs*, by Orford, which gives all the required information for making the different types.

The Huyghenian eyepiece is the one most universally used, and gives excellent definition and a wide field, but suffers from the defect of not being achromatic and has a rather curved field, so that an object is only in correct focus in the centre portion of the field. Fig. 29A shows an eyepiece of this type, sometimes known as a " negative " eyepiece. Both lenses are plano-convex, with the plane surface nearest to the eye.

The Ramsden or " positive " eyepiece is shown in fig. 29B, and consists of two plano-convex lenses similar to the Huyghenian, but the field lens has the convex surface nearest to the eye. It has not such a curved field as the Huyghenian, and is fairly free from distortion, but it has a pronounced chromatic difference of magnification, i.e. strong prismatic colours

are formed as the object moves from the centre of the field.

The solid type of eyepiece shown in fig. 29C gives a smaller field, but it is much flatter than either of the previously mentioned types, and does not suffer from the defect of

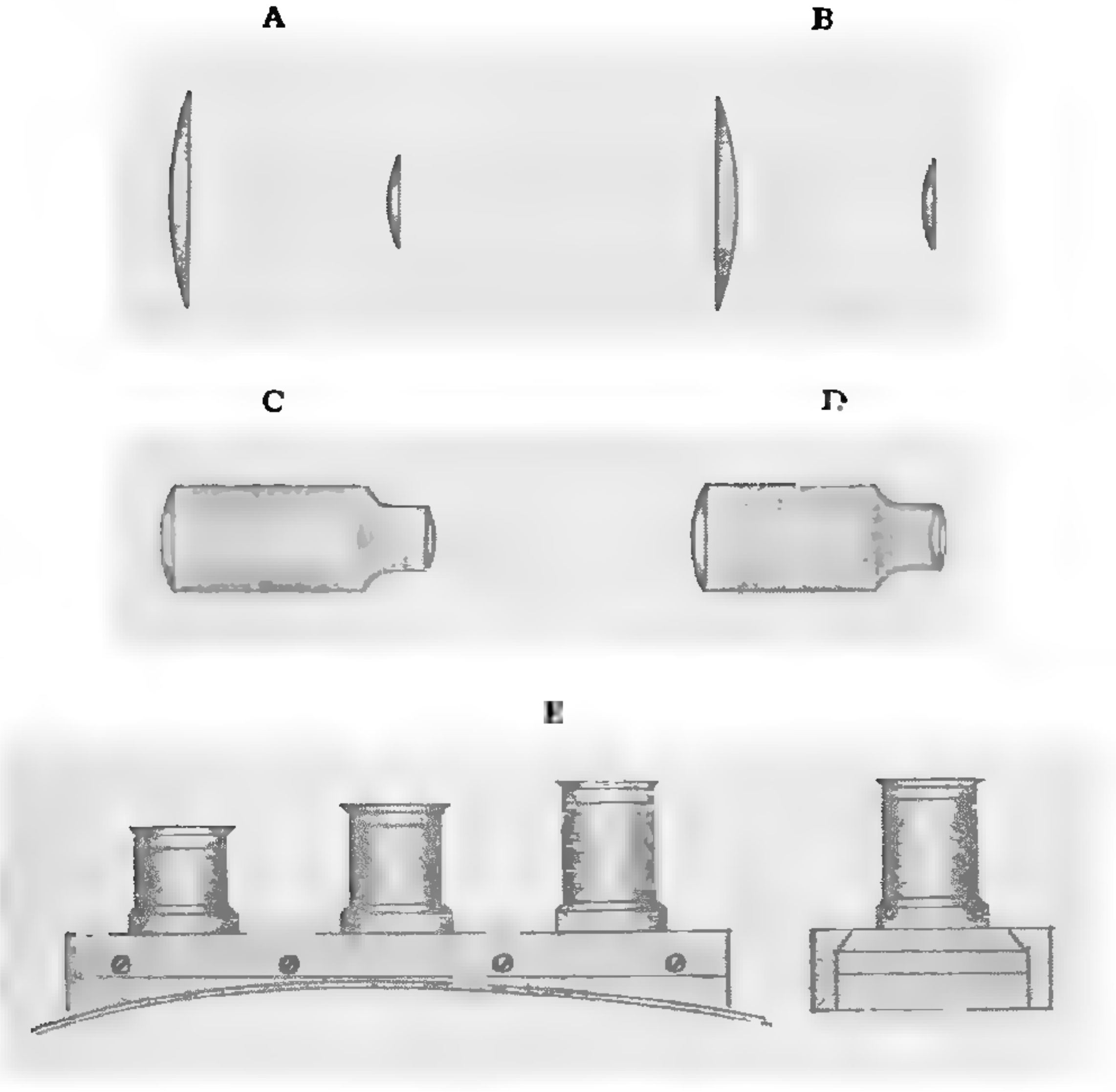


Fig. 29.—Eyepieces

A. Huyghenian. B Ramsden. C and D Solid. E. Eyepiece battery.

chromatic difference of magnification. An improvement in this type is made by constructing it from crown and flint glass as in fig. 29D.

The magnification of a telescope is governed by the focal length of the mirror, and the focal length of the eyepiece. The formula used is Fe/Fm, where Fm is the focal length of the mirror and Fe the focal length of the eyepiece. Thus,

if we use a 1-in. eyepiece on our mirror of 48-in. focal length, the magnification will be 48, and if we use a ½-in. eyepiece, the magnification will be 96, and so on. The *power* of a telescope depends entirely on the diameter of the mirror, and the greater the diameter the greater the power of the eyepiece that can be usefully employed. It is only on very good "seeing" nights, when the atmosphere permits of using a high-powered eyepiece, that it is possible to use a magnification of 50 to 80 times the diameter of the mirror.

If possible, a battery of eyepieces should be purchased, consisting of a 1-in., ½-in. and ¼-in., and these can be mounted on the telescope as shown in fig. 29.

CHAPTER X

Constructing and Mounting the Telescope

The Equatorial Mounting

In order that our telescope may be pointed to any area of the sky, it is obvious that it will have to be so mounted that it will be possible to rotate it in two planes, and this will require one bearing the axis of which is fixed in a permanent position, and another bearing with its axis at right angles to the first and fixed thereto. You will no doubt have observed that the stars and planets, as well as the sun and moon, " rise in the east and set in the west ". This is of course an apparent motion due to the rotation of the earth from west to east, so if we wish to observe and follow any of the stars by rotating the telescope on only one of its bearings, all that is necessary is to have the axis of that bearing parallel to the axis of the earth, so that by rotating the telescope in the opposite direction to that of the earth, the apparent motion is cancelled out. This type of mounting is known as the equatorial type, and is the one used for all astronomical telescopes.

The axis which is parallel to the earth's axis is known as the polar axis, and the one at right angles to it is the declination axis. The angle of the polar axis is obviously dependent upon the latitude in which the telescope is placed.

The types of mountings embodying the above principle are many and varied, but there are several points which are common to all mountings of good construction. Firstly, the main consideration is *rigidity*. Secondly, smoothness of rotation in the bearings. Other points are, correct setting up or alignment, both in the optical parts contained in the tube, and the setting of the axes, the elimination as far as possible

of air currents in the tube, and if photographic or spectroscopic work is contemplated, the provision of a suitable mechanical drive.

The first essential of rigidity can be obtained by making the bearing surfaces of ample dimensions, and smoothness of

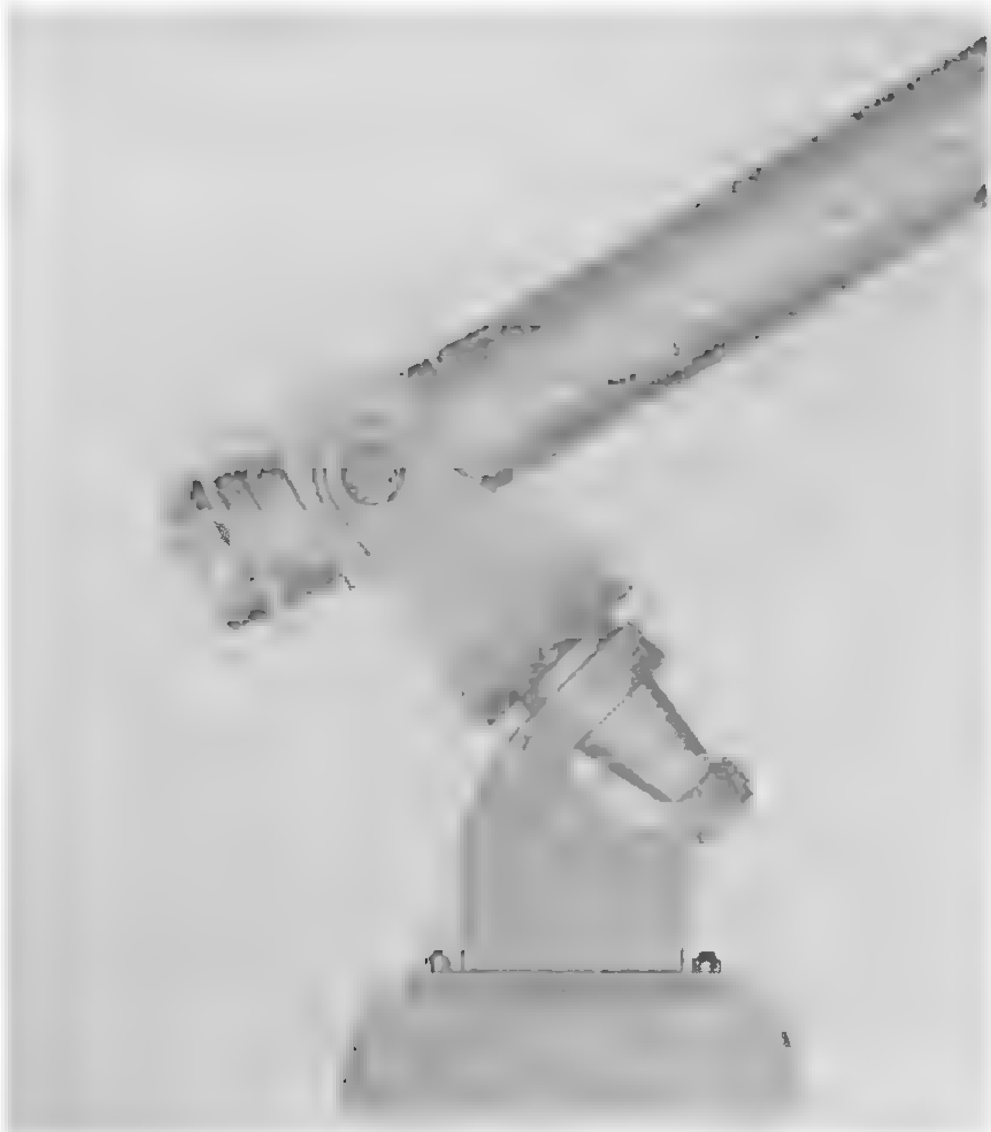


Fig. 30 —Fork type mounting

rotation by using ball bearings wherever possible. A flimsy mounting can spoil all the pleasure of using the telescope, and for accurate work is worse than useless. Far too many telescopes are made which sacrifice rigidity for appearance, and whilst the ideal is to combine the two, it is far better to have a rigid mounting made from discarded motor parts and concrete, than to have a flimsy one made with beautifully

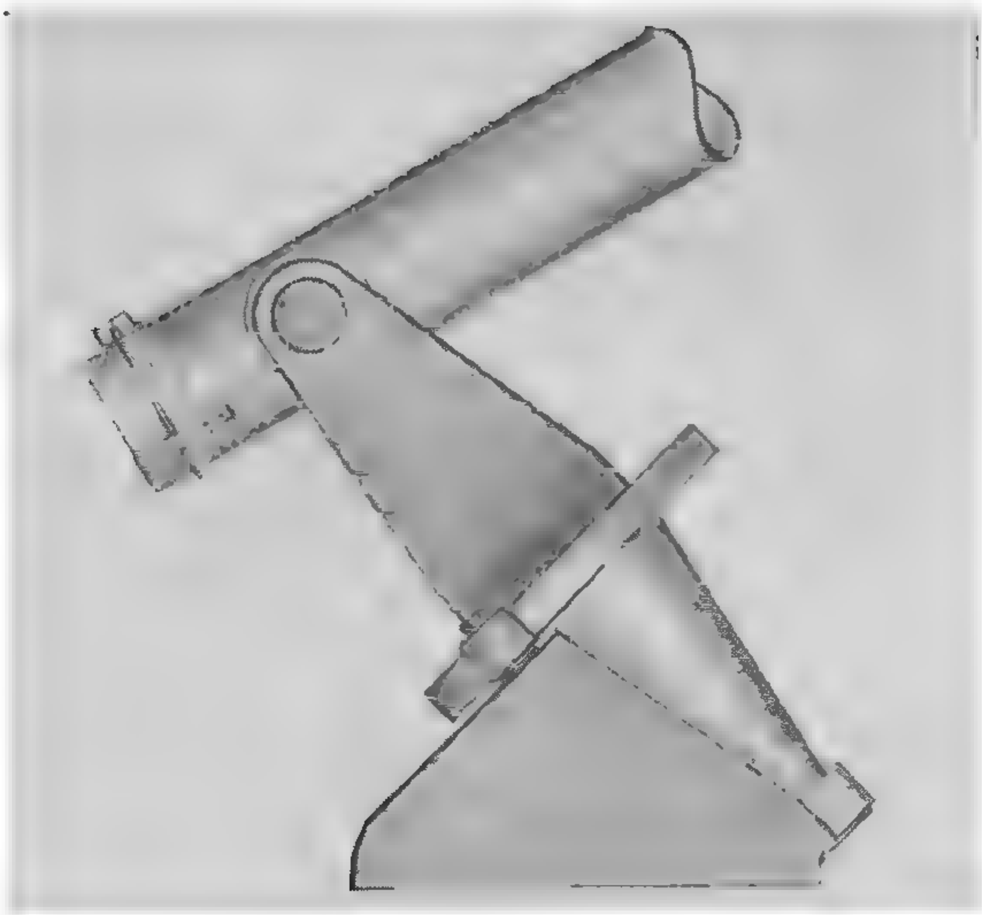


Fig. 31.—Fork type mounting

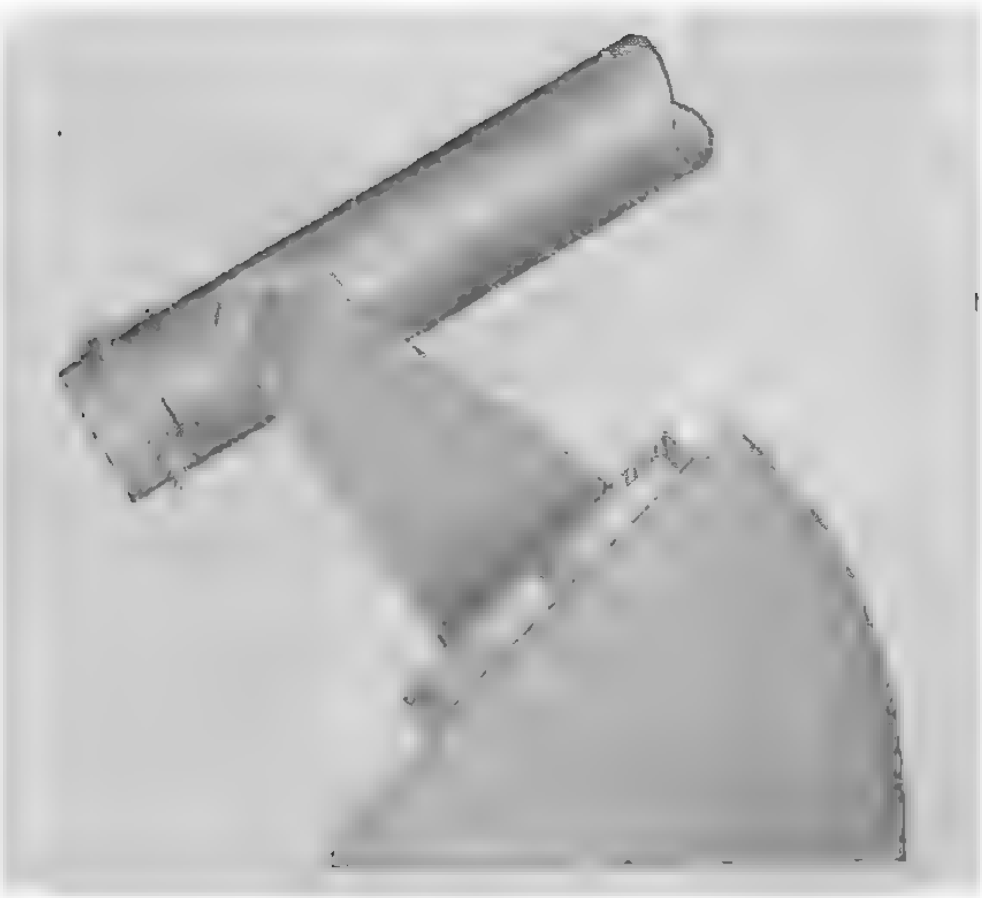


Fig 32.—Fork type mounting

polished brass and chromium plating, which the slightest breeze will cause to shake and dither.

The following sketches illustrate some of the mountings which have been constructed from time to time, and we will start off by discussing their merits and demerits. There are

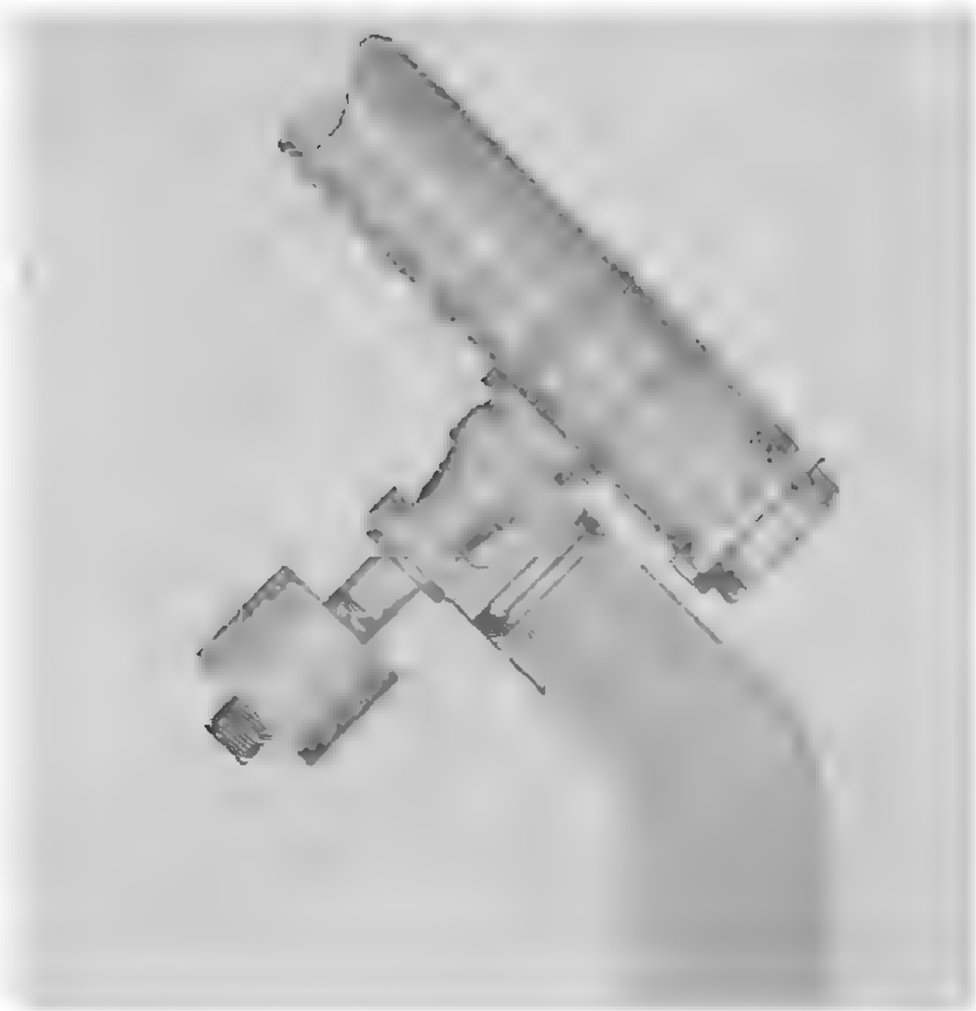


Fig. 33.—Counterbalanced type mounting

two main types, the Fork or English type in which the telescope tube is mounted so as to come directly over the polar axis, and the Counterbalanced or German type, where the tube is mounted to one side of the polar axis and is counterbalanced by means of a weight at the other end of the declination axis. The following is a brief survey of the illustrations given, with notes on some of the points to be observed.

1. This is a well-known fork type of mounting, and in its construction it should be borne in mind that the weight of

the telescope overhangs the polar axis bearing, so that the fork should be of ample proportions and its length reduced to a minimum so that there is just sufficient room for the telescope tube to rotate between the forks without fouling

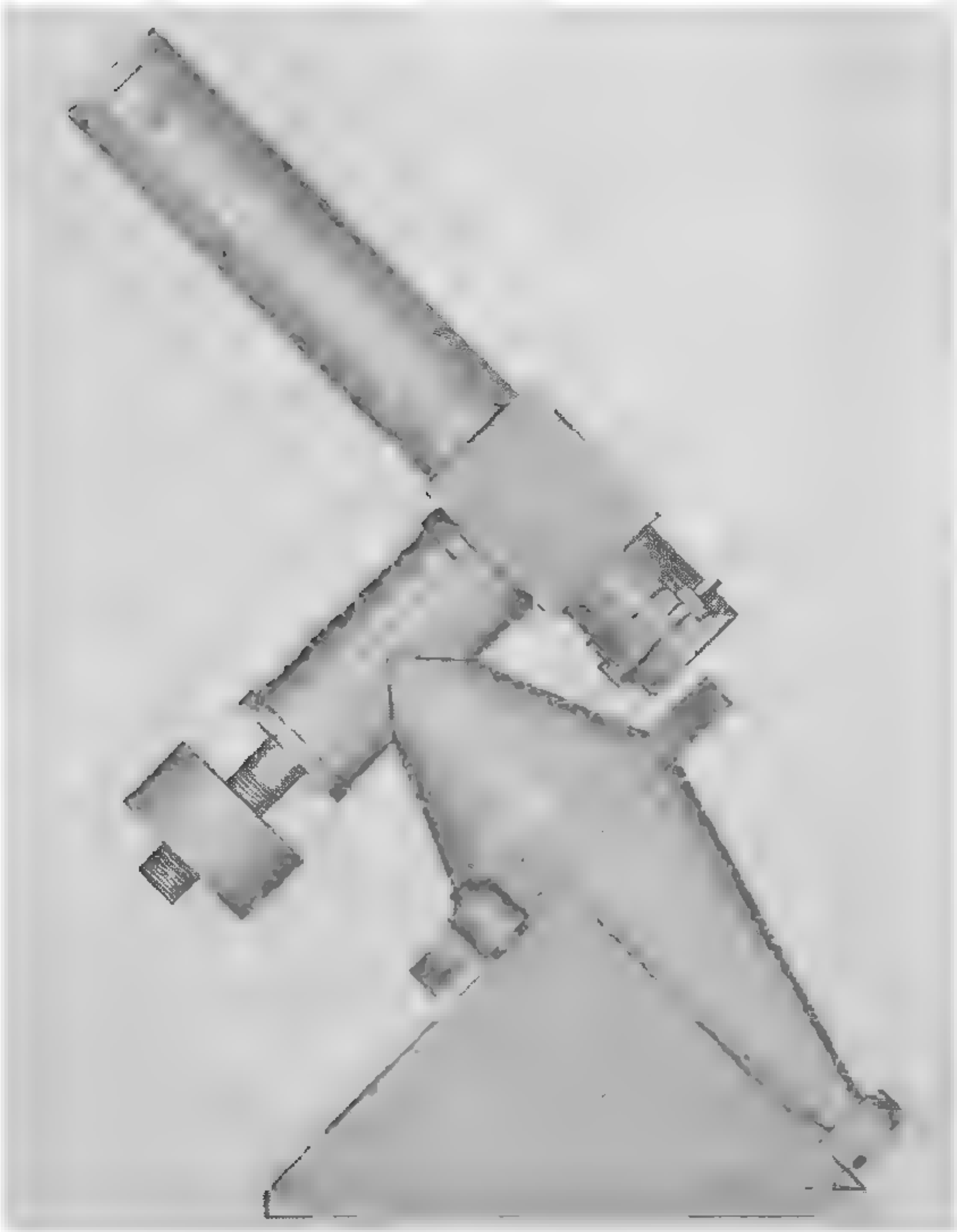


Fig. 34.—Counterbalanced type mounting

the bottom of the fork. The main polar axis bearing should also be of ample size, and preferably of the cone type (fig. 30).

2. This type is similar to the above, but the main polar axis bearing is extended to bring the centre of gravity of the tube within the bearing, thus making for better rigidity. The

outer rim of the bearing should of course be accurately machined so that it will rotate smoothly on the rollers. The small rollers can be easily adapted to give a slow motion to the axis either by hand or mechanical means (fig. 31).

3. This shows another method of extending the polar axis bearing whilst still preserving a good bearing surface (fig. 32).

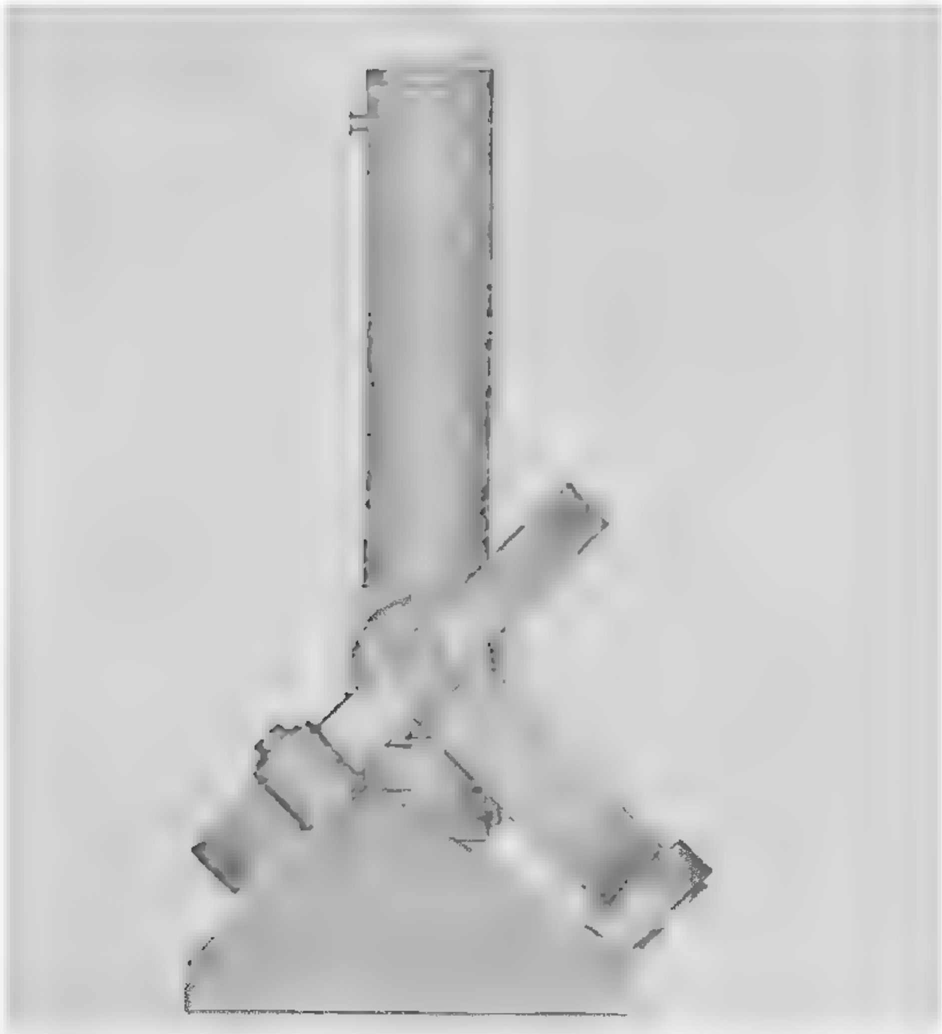


Fig. 35.—Split-ring type mounting

4. A typical counterbalanced type, and here again the need is stressed for bearings of ample proportions. Pipe fittings can be usefully employed in its construction, but they should not be less than 4 in. internal diameter (fig. 33).

5. A suggested modification of the counterbalanced type made from sheet metal and concrete, embodying the large polar axis bearing rotating on rollers (fig 34).

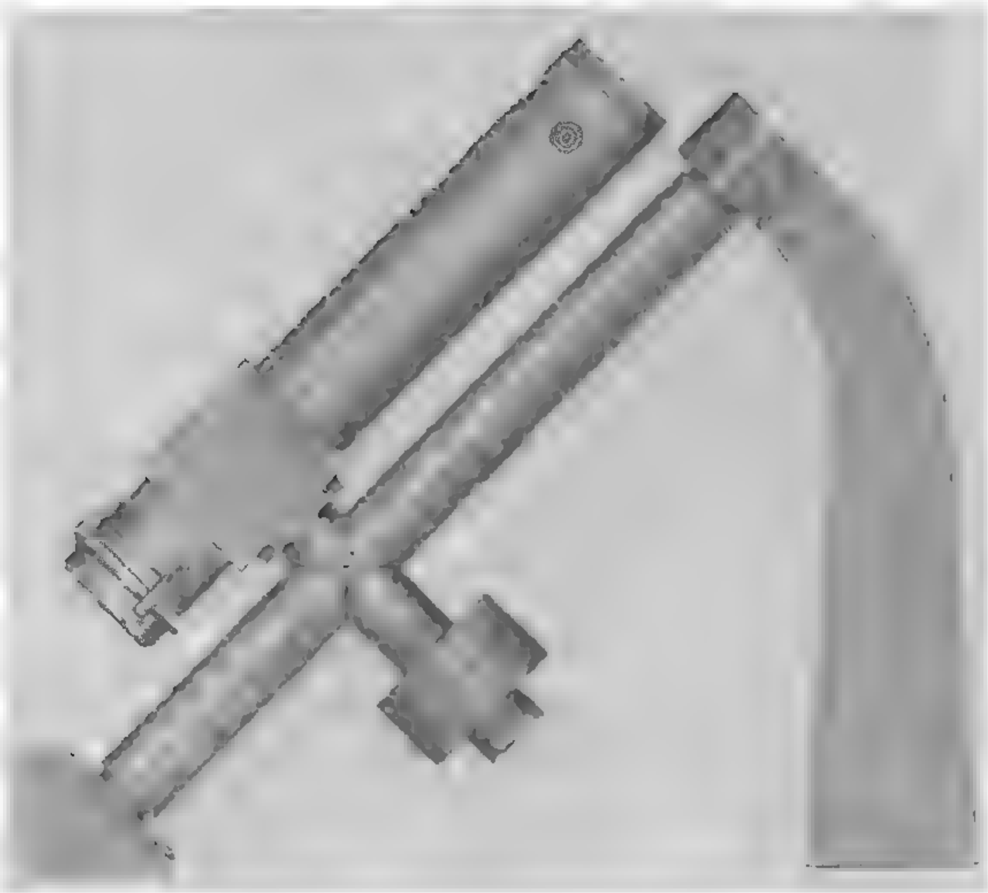


Fig. 36.—Counterbalanced type mounting

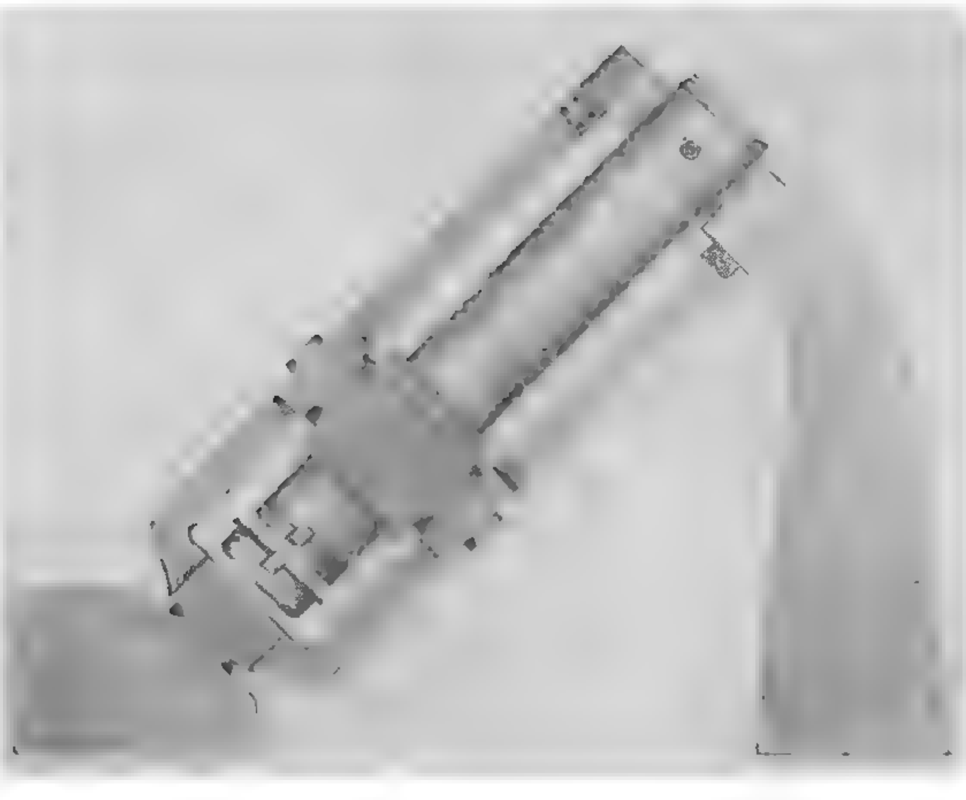


Fig. 37.—Long fork type mounting

6. The split-ring type, which can be constructed to give a very rigid type of mounting (fig. 35).

7. Another form of the counterbalanced type with the declination axis between the two bearings of the polar axis. A good solid mounting (fig. 36).

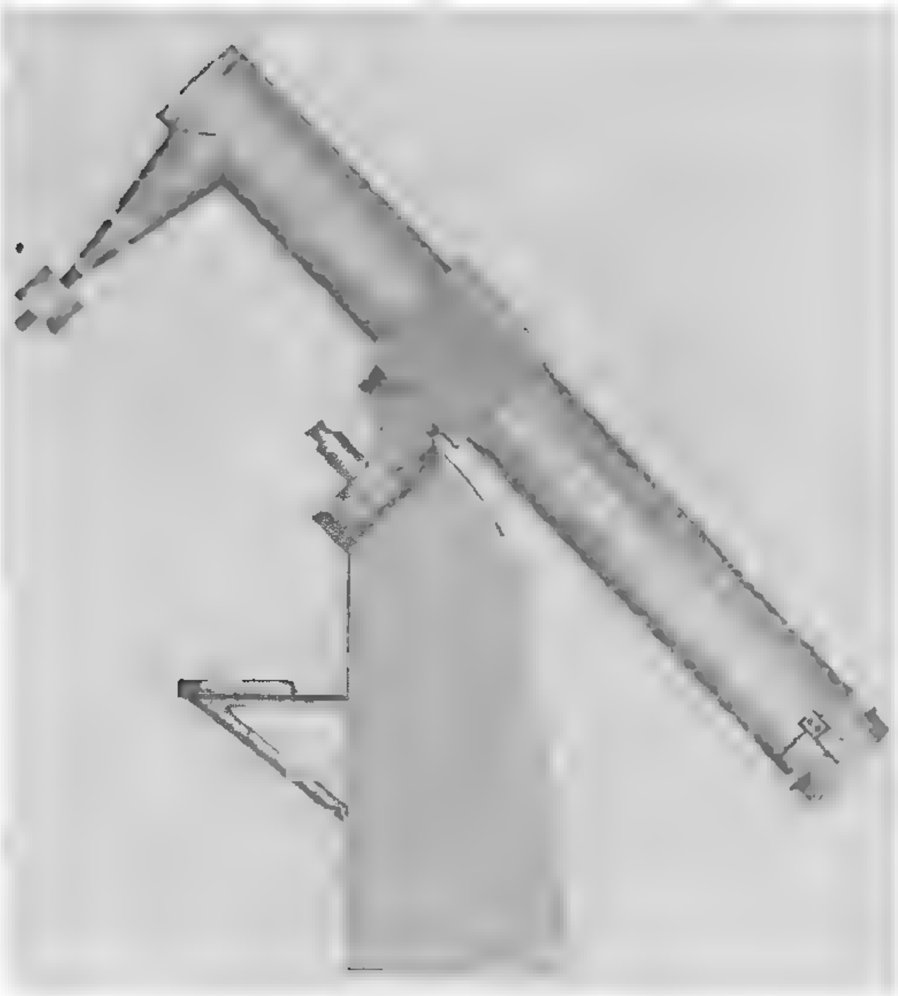


Fig. 38.—Springfield type mounting

8. Similar to No. 7, but with the tube non-counterbalanced and a split ring for the upper polar axis bearing which allows the telescope to be pointed to the polar region of the sky (fig. 37).

9. This is known as the Springfield type, and its main feature is that the observer remains in one position the whole time, the eyepiece being in direct line with the polar axis. This type necessitates an additional reflecting surface in the form of a prism or diagonal (fig. 38).

It will be seen from a study of the above mountings that there is plenty of scope for originality of design, and the type chosen usually depends on what materials are most readily obtainable. Whatever type is chosen, always bear in mind that rigidity is of paramount importance.

The Mirror Cell

In order that the mirror can easily be removed from the tube for safe keeping when not in use, and for the purpose of ease in assembly, it will be necessary to provide a suitable casing or cell. Next to having a casting specially made, a brake drum from a motor car forms an ideal cell for mirrors up to 10 or 12 in. in diameter. It is sufficiently rigid without being too heavy, and very little work is required on it to adapt it to our purpose. Fig. 39 shows a method used by the writer, which was found to be very satisfactory in use. The three-point suspension is quite sufficient for mirrors up to 10 in. diameter, provided their thickness is at least $\frac{1}{8}$ of the diameter, and the three disks are made from $\frac{1}{4}$-in. leather. The distance pieces separating the mirror from the wall of the drum are made from hardwood with a leather or hard felt facing, and are fixed to the cell through holes drilled in the wall, by screws. On the top of the distance pieces are fixed shaped brass holding down plates which fit snugly against the bevel of the mirror. A clearance of about ·002 in. should be allowed at all points where the mirror touches the distance pieces and the holding-down plates, to allow for expansion and contraction. If the mirror is held too firmly there will be a danger of distortion through changing temperature, but on the other hand the play should not be such as to make any appreciable difference in the optical train.

Slots are cut in the rim of the cell to clear the lugs on the telescope tube, and in fixing the cell to the tube the cell is rotated through about 60° so that the rim is engaged in the slots of the lugs, and is held in position by the clamping screws. Adjusting screws fitted with lock nuts, opposite to the clamping screws, enable the optical axis of the mirror to be squared on with the axis of the tube. One of the lugs

should be marked, and a corresponding mark made on the rim of the cell, so that the cell is always assembled in the same position.

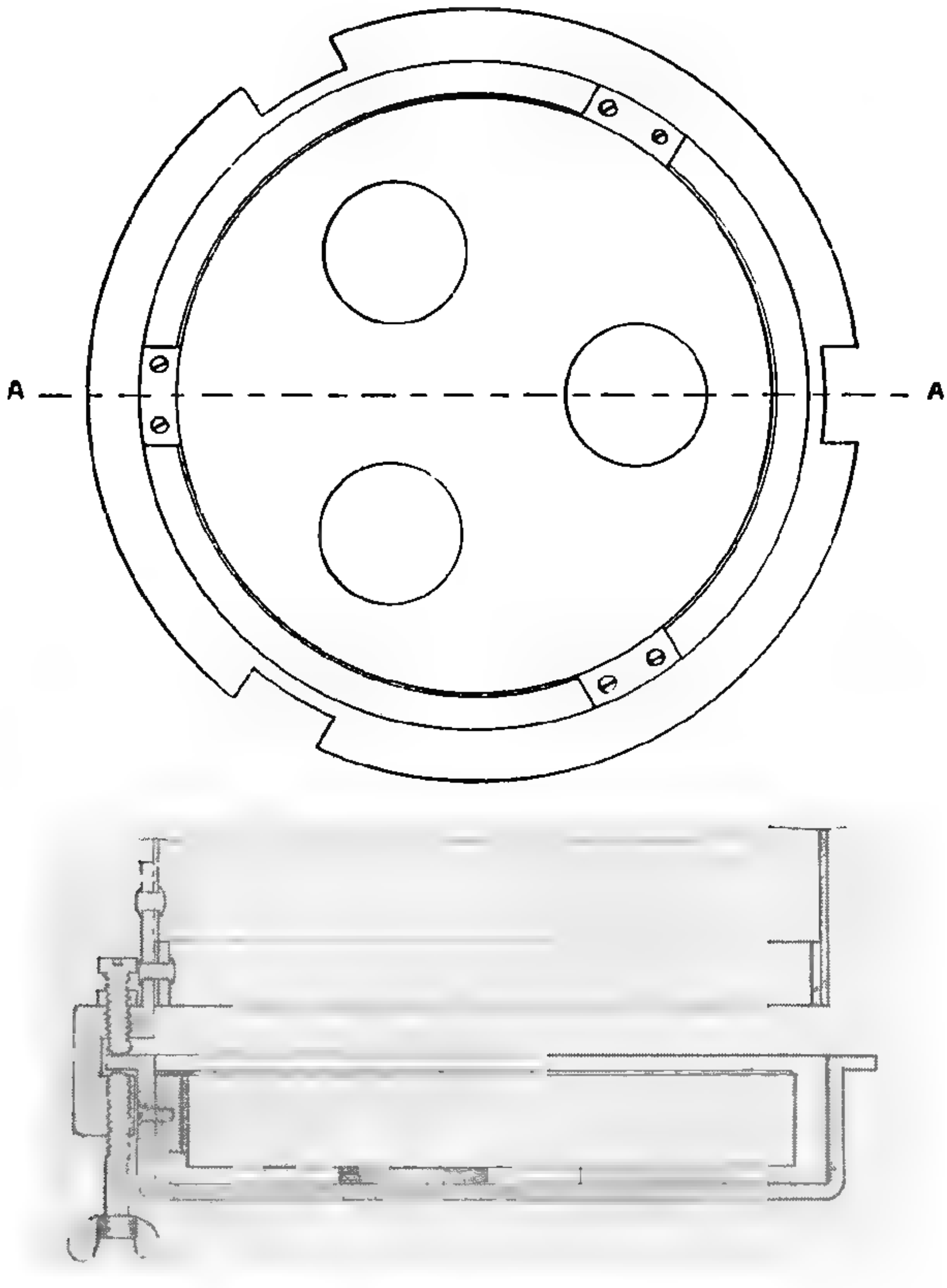


Fig. 39.—The mirror cell

It is, of course, possible to make a similar type of cell from plate mild steel or brass, but the joints should be welded or brazed so as to form a really rigid case for the mirror.

To preserve the silvered surface of the mirror as far as

possible when not in use, a cover as shown in fig. 40 should be made, and lined with blotting paper or flannel to absorb the moisture contained in the air space of the cell. If you make a point of placing this cover in a warm oven or in front

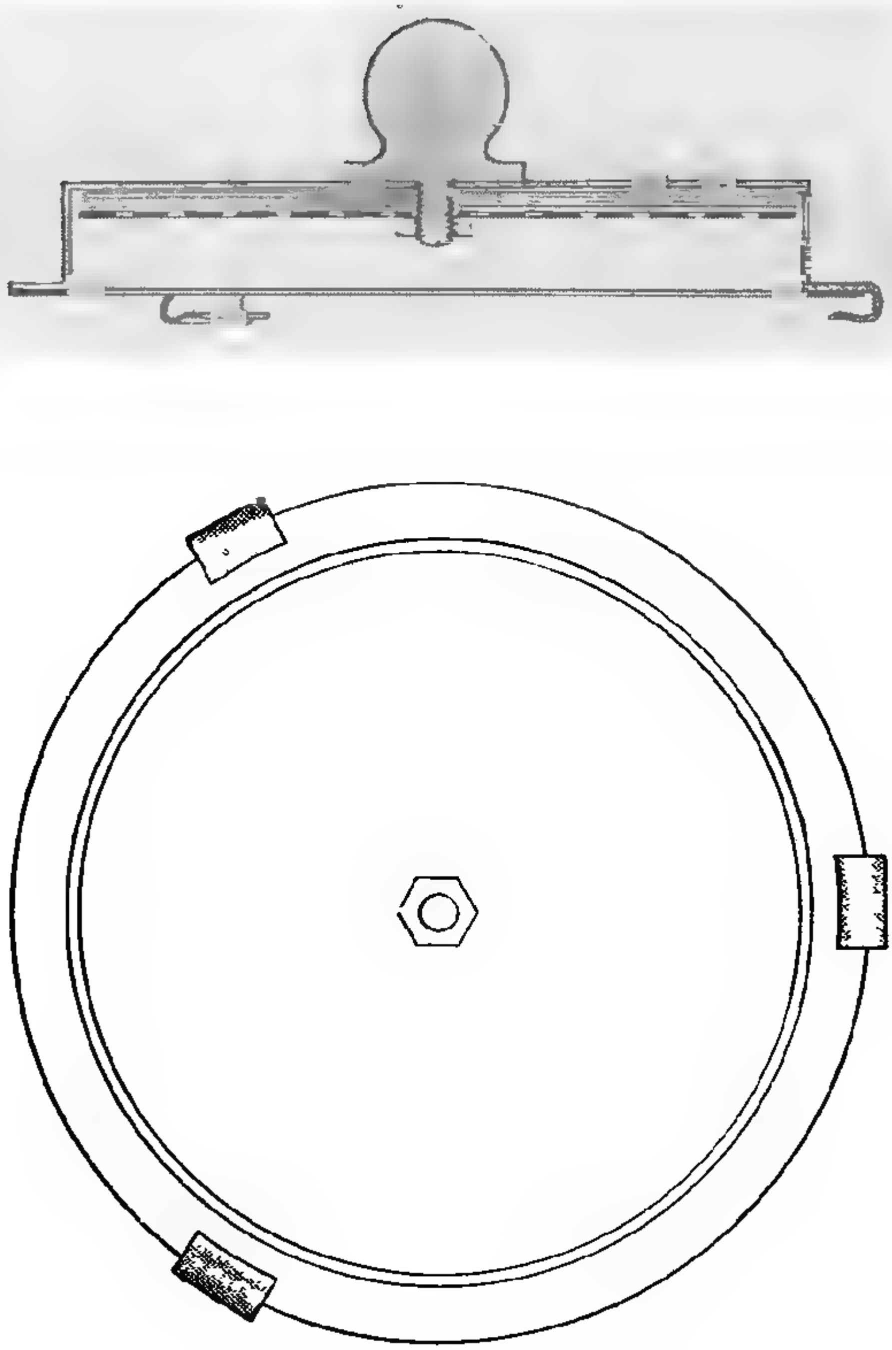


Fig. 40.—The mirror cover

of a fire in order to dry it out thoroughly whenever the mirror is in use, you will find that the life of the silvered surface will be considerably longer than would be the case if it were left to the mercy of the atmosphere. The jointing ring

should not be of rubber, as this contains some free sulphur which may attack the silver. Thick paper or cardboard serves very well.

The Telescope Tube

For some reason or other, probably æsthetic, the popular conception of a telescope is of a shining brass tube in which is mounted the optical components. There is no doubt that brass looks very nice, but it is not necessarily the best material from the point of view of efficiency in use, and in any case, for a telescope of anything over 4 in. in diameter, the cost of the brass tubing would be prohibitive, and it is doubtful whether it could be obtained in the size required for a 6- or 8-in. mirror.

In choosing the material from which to construct the tube, account must be taken of how the telescope is going to be housed. If it is to be erected in a properly constructed observatory, then its weather-resisting properties need not be considered, and it can be made from whatever material is most readily obtainable. In most cases, however, the amateur's telescope is housed in a shed of wooden or galvanized iron construction, or even left out in the open with a tarpaulin to protect it from the direct effects of rain or snow. Sheet iron is generally easy to obtain, and a good rigid tube can be made from this in practically any size with suitable reinforcement in the form of steel rings. If this material is used, it should be given a good undercoat of red lead and boiled oil.

The main point to be borne in mind in the construction of the tube, apart from rigidity, is that of air currents, which tend to form on the inside of the tube and close to the mirror, which are caused by varying temperature in the atmosphere and the telescope. These can be very detrimental to the power of definition of the telescope, and every step should be taken to reduce them to a minimum by efficient ventilation of the tube and suitable insulation. There are two main types of tube, one in which the tube is totally enclosed, and the other in which the tube is of an open or lattice-work construction. The open type does not suffer from the air currents

which form in an enclosed tube, but in the Newtonian type of telescope where the observer is generally standing at the side of the tube, this advantage is offset to some extent by reason of the warm air currents from his body, which float across the tube and produce a similar effect.

Another important point is that of dewing, caused by a sudden increase in the temperature of the atmosphere with a consequent deposit of moisture on the diagonal or mirror. This can be avoided to a large extent by insulating the part of the tube nearest to the diagonal or mirror with cork or felt. If dewing should take place whilst observing, the best policy is to remove the optical parts from the tube and place them under their covers until such time as the moisture has been absorbed by the pad inside the cover. Needless to say, the silvered surface should never be wiped, as this would inevitably damage the coat of silver.

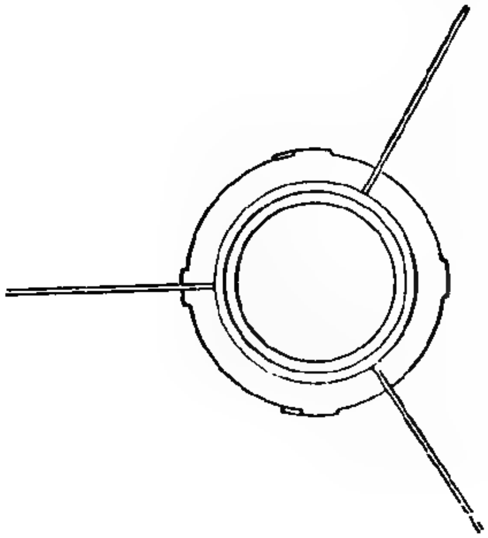
Provision should also be made for rotating the tube about its axis, otherwise it will be found in using the telescope that sometimes the eyepiece comes into a very awkward position for observing. The same effect could be obtained by mounting the diagonal and eyepiece on an independently rotating collar, but unless this is accurately made there is the danger of upsetting the optical axis of the telescope every time the collar is moved to a new position.

There is much to be said in favour of a wooden tube, which if properly constructed will be found to be very free from the undesirable air currents mentioned above, and is less likely to promote dewing. Whatever type of tube is constructed, it should be at least an inch wider in diameter than the mirror, and in the enclosed type the mirror should be mounted with a gap between the mirror and the tube to allow the air to circulate freely.

The Diagonal Holder

The most convenient method of mounting the diagonal or prism is by means of three arms as in fig. 41. The arms are made from hard brass strip, and are fixed to a short length of brass tubing at points 120° apart around its circumference

The outer end of each arm is provided with a short length of threaded brass rod, which projects through the wall of the tube and is held in position by means of a nut. By making the hole in the tube in the form of a slit, it is possible to



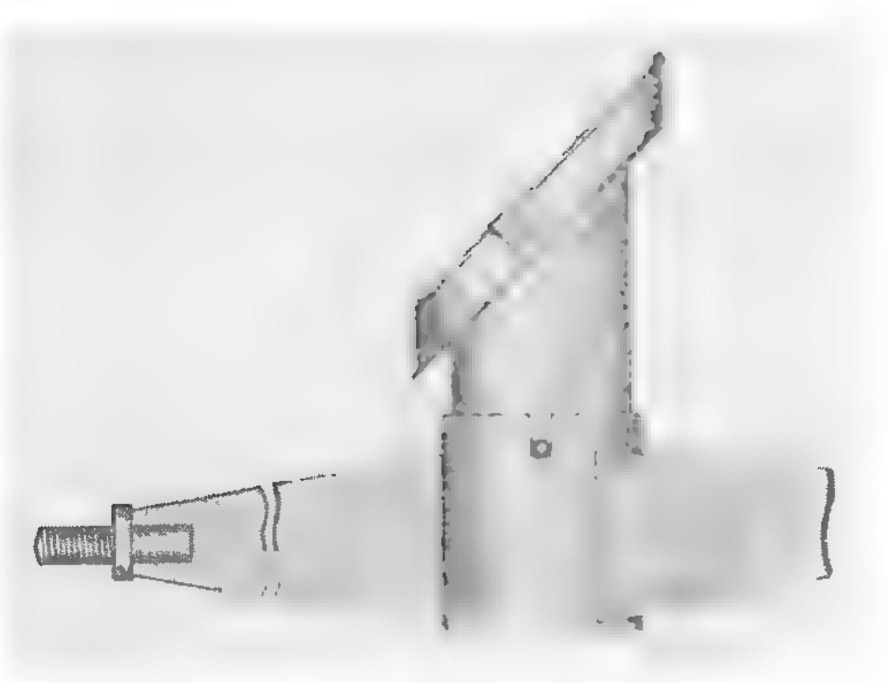


Fig. 41.—The diagonal holder

adjust the position of the diagonal to the optical axis of the mirror. The diagonal is mounted on a brass plate provided with securing clips as shown, to which is soldered a length of brass tube, which will fit snugly into the tube carrying the

arms. The optical axis of the mirror should be brought square on with the axis of the tube, and the diagonal adjusted to project the rays to the eyepiece. The brass tube holding the arms should be slotted to receive a pin fitted to the tube holding the diagonal. By this means you will be assured that the diagonal is always placed in the same position when setting up the telescope.

To preserve the silvered surface of the diagonal when not in use, solder a short length of brass tubing, of the same diameter as that used for the centre piece of the arms, to the inside of a lid of a tin of sufficient size to accommodate the whole of the diagonal. The tin should be of the lever-top type, and by lining the bottom with paper or felt you will have a container similar to that constructed for the mirror.

Bearings

As previously pointed out, the polar and declination axes should be of robust construction, and although perhaps the best method is to have castings made and turned, there are several standard fittings and parts that can be used from various machines, cars, &c., and adapted to make a rigid mounting. The rear axle of a car lends itself very well to our purpose, being of ample rigidity for a 6-in. to 8-in. telescope, and the studs on which the wheel is fixed form a good support for the tube.

Plain metal bearings, whilst not having the same ease of movement as roller or ball bearings, are quite suitable for a telescope mounting, and are very often more easily adaptable when it comes to providing a means of clamping the bearing to hold the telescope in one position. In place of expensive castings it is quite possible to contrive very serviceable bearings from light section tubing and concrete.

In using pipe fittings for bearings it should be remembered that the threads are tapered, and consequently there will be some play as the bearing is rotated. This can be minimized by grinding the threads, and as the polar and declination axes are never turned through more than 180° in use, the slight play will not be serious if the grinding is efficiently carried out.

Setting Circles

In order to get the full benefit from the telescope, it is essential to fix graduated circles to the polar and declination axes. Although it is quite easy to pick out the planets and

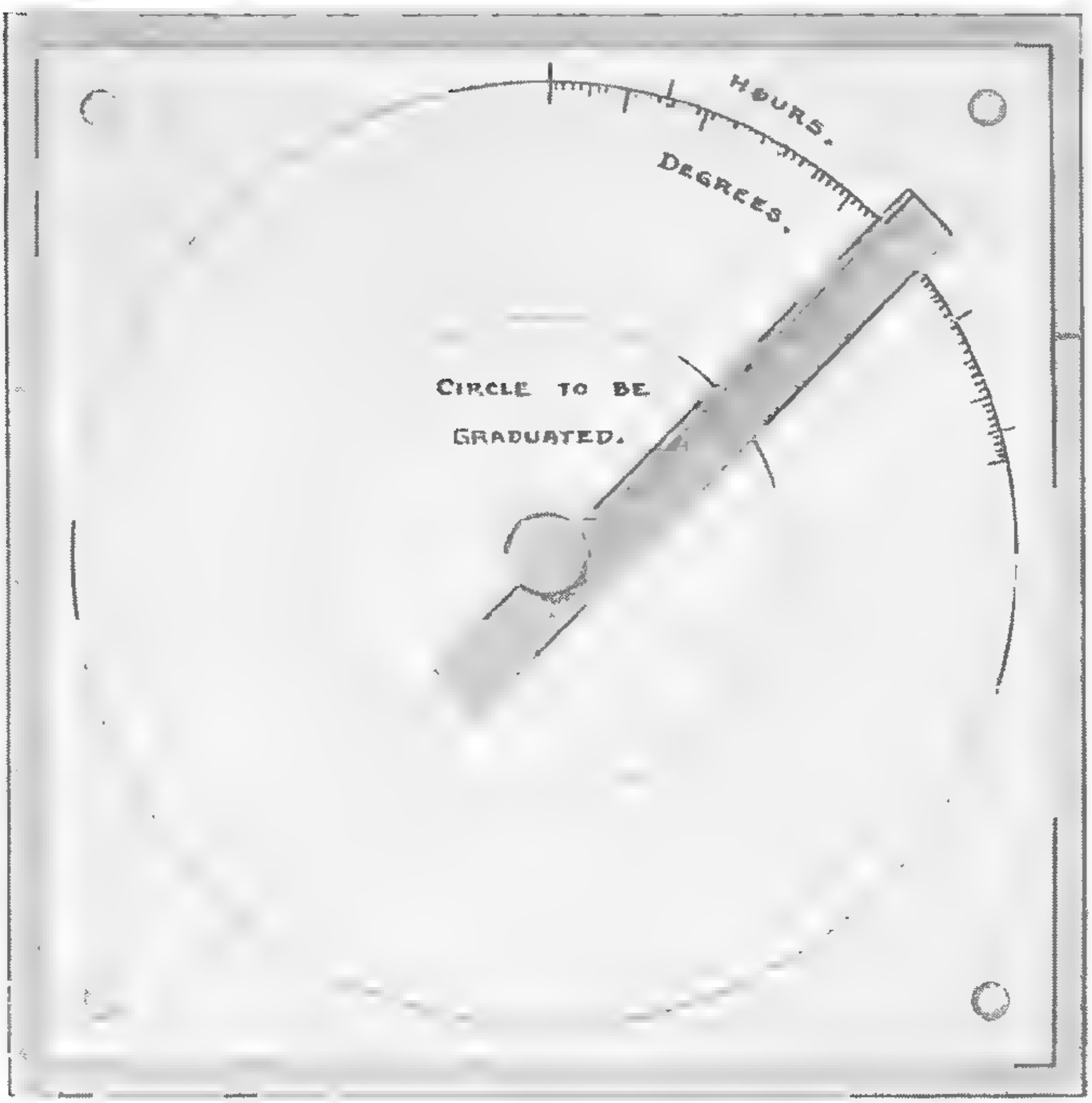


Fig. 42.—Graduating the setting circles

some of the brighter stars, it is difficult and sometimes impossible to locate an obscure double star, or a comet, or cluster or nebulæ unless setting circlcs are fitted to the telescope. The circle on the polar axis is divided into twenty-four divisions, each representing one hour, and these are again subdivided into minutes. The declination axis circle is divided into 360° in much the same manner as a protractor. (A large

accurately made protractor serves very well for this purpose.)

Although brass gives a "finished" appearance, the material used for the setting circles is not important, and zinc sheet, celluloid, or even paper which is varnished over when the graduations have been marked on in Indian ink, will be found quite serviceable. There is no need to go to extreme fineness in marking the circles, and one-degree markings on the declination axis circle and four-minute markings on the polar axis circle will be accurate enough for finding any object in the sky. If you have a lathe fitted with a dividing head, the marking of the circles will be quite a simple matter, but failing this a pair of dividers and a straight-edge will serve to make quite accurate circles. A method of marking the circles is given in fig. 42, where the circle is first drawn on paper to a size larger than that required for the finished circles, which are then marked off *inside* the paper circle so as to reduce any error to a minimum. If the paper circle is marked off into 360 divisions, this can be used for both the declination and the hour circle. ($\frac{24 \times 60}{360} = 4$ min.)

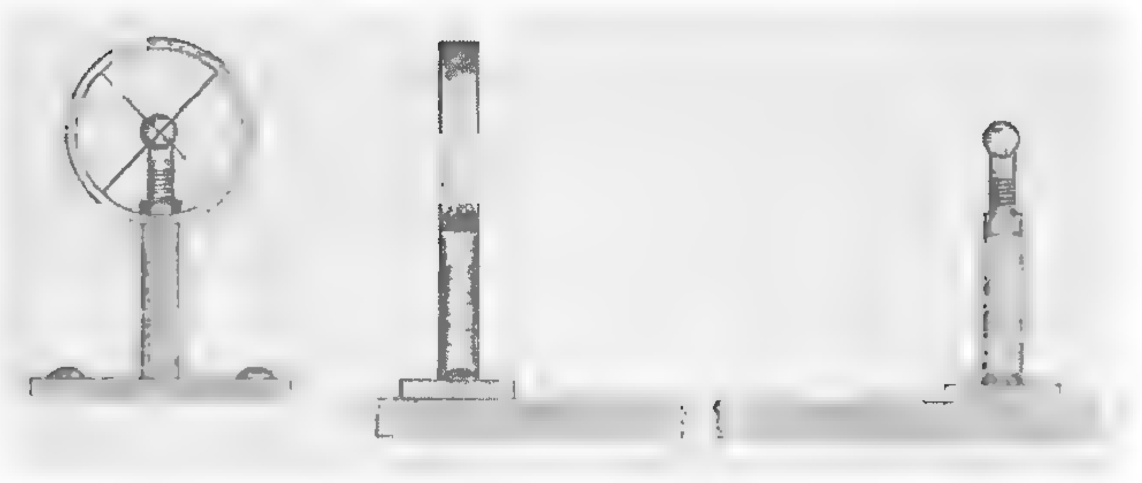


Fig. 43.— Finder (gun-sight type)

The Finder

Pointing the telescope to a star may seem simple enough, but you will find as soon as you start to use the telescope that it can be a very trying business unless the telescope is equipped with some form of finder. The easiest type to construct is shown in fig. 43, and is very similar to an ordinary

gun sight. It can be best mounted on the box carrying the telescope tube, and provision should be made for adjusting it to correspond with the optical axis of the telescope.

Another type is in the form of a refractor telescope with a fairly wide field, and with cross hairs situated in the eyepiece. This need not be expensive to construct, as there is no need for it to be achromatic, and the writer has constructed one from odds and ends of brass tubing, a spectacle lens serving for the objective, and two small plano-convex lenses picked up on a second-hand stall used for the eyepiece. The lay-

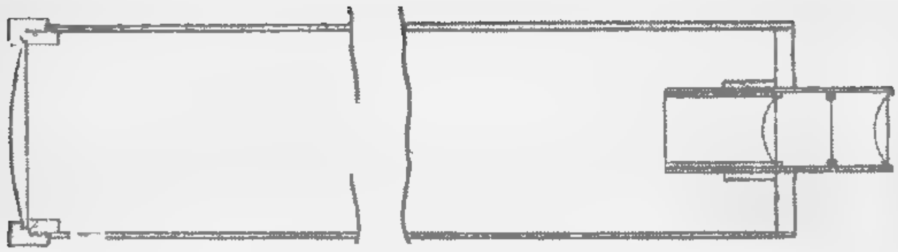


Fig. 44.—Finder (telescope type)

out of this finder telescope is given in fig. 44. The cross hairs can be made from a piece of finely drawn glass rod, or an alternative method is to dab a small quantity of rubber solution on one side of the supporting ring with a match stick, and draw the thread of rubber across to the opposite side, and then repeat the procedure to form another thread at right angles.

In lining up the finder, the telescope should be pointed to a fairly bright star (preferably the Pole star, if the telescope is not fitted with some form of drive), and brought into the centre of the field of the main telescope, and the finder then adjusted so that the star is bisected by the cross hairs.

Driving the Telescope

The most striking effect observed on looking through a high-powered teles ope for the first time, is the very rapid apparent motion of he star or planet across the field of view,

caused of course by the rotation of the earth. Assuming the telescope to have an angular field of half a degree (roughly the diameter of the moon), the time taken for a star to travel across the field of view will be

$$\frac{24 \times 60}{360 \times 2} = 2 \text{ min.}$$

It is obvious, therefore, that if it is desired to observe an object for any length of time, provision must be made for rotating the telescope evenly to counteract the rotation of the earth. The most efficient method of doing this by hand is to incorporate a reduction gearing in the polar axis either by means of a train of gears or a worm wheel. A friction clutch should also be attached, so that the slow-motion drive can be disengaged when it is desired to swing the telescope through a large angle. The wheel or handle operating the drive will in most mountings have to be extended to a convenient position for operating whilst observing at the eyepiece end of the telescope, and this is quite easily carried out by means of a flexible drive.

This slow-motion drive will be found quite satisfactory for visual observation, but if photography is to be attempted some form of mechanical drive will be necessary. One of the most easily adaptable forms of drive is a gramophone motor. Suitable gearing will have to be added to reduce the speed of the drive and a friction clutch incorporated as for the hand drive. Some form of hand control will still be necessary to compensate for constructional inaccuracies, different refraction of the atmosphere at varying angles, &c., and in the clockwork motor drive this can be fitted to the speed control.

If you have electricity laid on in your observatory the ideal method of driving the telescope is by a fractional horse-power electric motor suitably geared down. Not only will it give you a smooth drive, but you will also be able to devise an accurate clock which can be made to record star time.

CHAPTER XI

Setting up and adjusting the Telescope

The pier or column on which the telescope is mounted should be based on solid ground. If you have a wooden floor to the observatory the pier should be carried down through the floor to rest on the ground. A substantially built reinforced concrete pier is hard to beat, and it should be tapered outwards at the bottom and continued below ground level to a point well below the frost line. Before setting the pier, so that the polar axis is parallel to the axis of the earth, it will be necessary first of all to adjust the optical components of the telescope, and to ensure that the declination axis is at right angles to the polar axis.

First of all, fix the mirror and diagonal to the tube and then, standing behind the diagonal, see if the reflection of the diagonal is in the centre of the mirror. If it is too much to the left, then slacken off the adjusting screw on the left-hand side of the mirror, or tighten up the adjusting screws on the right-hand side. Continue the adjustments until the reflection of the diagonal is in the centre of the mirror, and then tighten up the lock nuts on the adjusting screws (fig. 39).

Next, place the eyepiece in position with the lenses removed. On looking through the tube of the eyepiece you should see the mirror reflected in the diagonal and situated centrally in relation to the eyepiece tube. Also you should see the reflection of the diagonal in the mirror, and this also must be central. If there is any departure from these conditions, adjustment of the diagonal holder will be required by moving the arms along the slots provided in the telescope tube, so as to bring the diagonal to an angle of 45° with the mirror, and with the

eyepiece. Make absolutely sure that all the optical parts are "squared on", otherwise no matter how carefully youı mirror has been made you will get distortion of the image in the form of a flare on one side if the optical parts are not in correct relation to each other.

The next step is to check up on whether the optical axis of the mirror is at right angles to the declination axis. Set the telescope tube so that it is in a horizontal position and looking through the eyepiece, focus a thin stake or plumb line at a distance of about 30 to 50 yd. away, so that it is in the centre of the field. Fix a length of thin string to the stake or line and bring it back to the telescope, so that it is in line with the axis of the tube, and extend it beyond the telescope to a point 30 to 50 yd. behind the telescope and affix another stake or plumb line. Remove the string between the two stakes, and then swing the tube through 180°, so that it is pointing to the second stake. If the optical axis of the tube is at right angles to the declination axis, the second stake will appear in the centre of the field. If it is not, insert shims between the telescope tube holder and the point where it is fixed to the mounting until both stakes appear in the centre of the field.

To set the polar axis parallel to the axis of the earth, place the declination axis in a horizontal position, with the tube pointing to the north, and pick up the north pole star in the field of the telescope by swinging the tube on the declination axis and moving *the whole mounting*. (The position of the declination axis relative to the polar axis must not be disturbed.) This adjustment should be made when the true pole is above or below the north pole star (see fig. 45). Six hours later, when the pole star has revolved through 90°, revolve the declination axis through 90°, so that it is in a vertical plane, and clamp in position. The telescope tube can now be rotated from east to west, and the pole star, being at the same altitude as the true pole, should be made to pass through the centre of the field by tilting the whole mounting. The north pole star is just over 1° from the true pole at a point nearer to Cassiopeia, as shown in fig. 45.

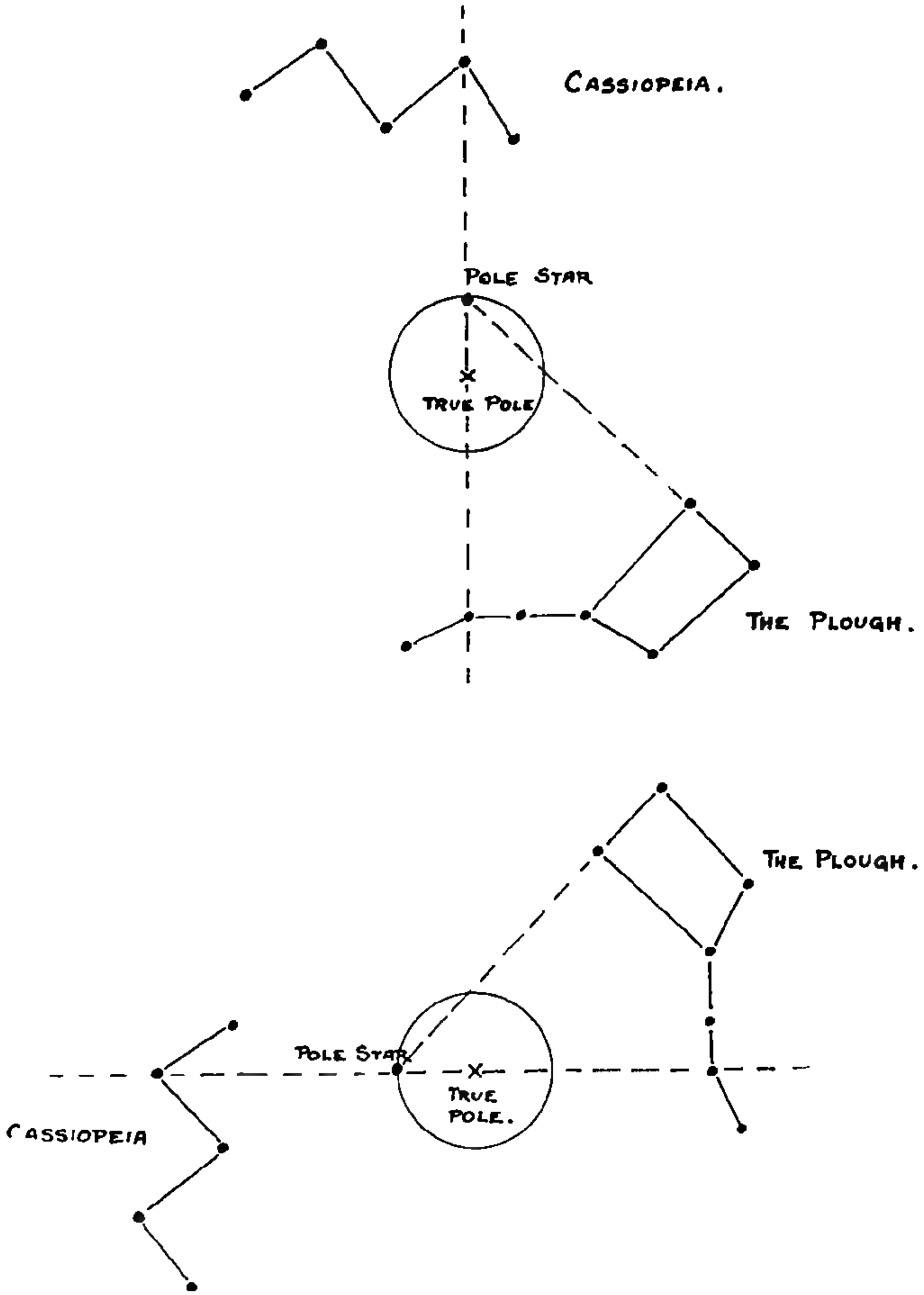


Fig. 45.—Position of true pole

Telescope Housings

The conventional method, and the most satisfactory, of housing a telescope is to build a brick or concrete base with a revolving hemispherical dome. The cost of such a building

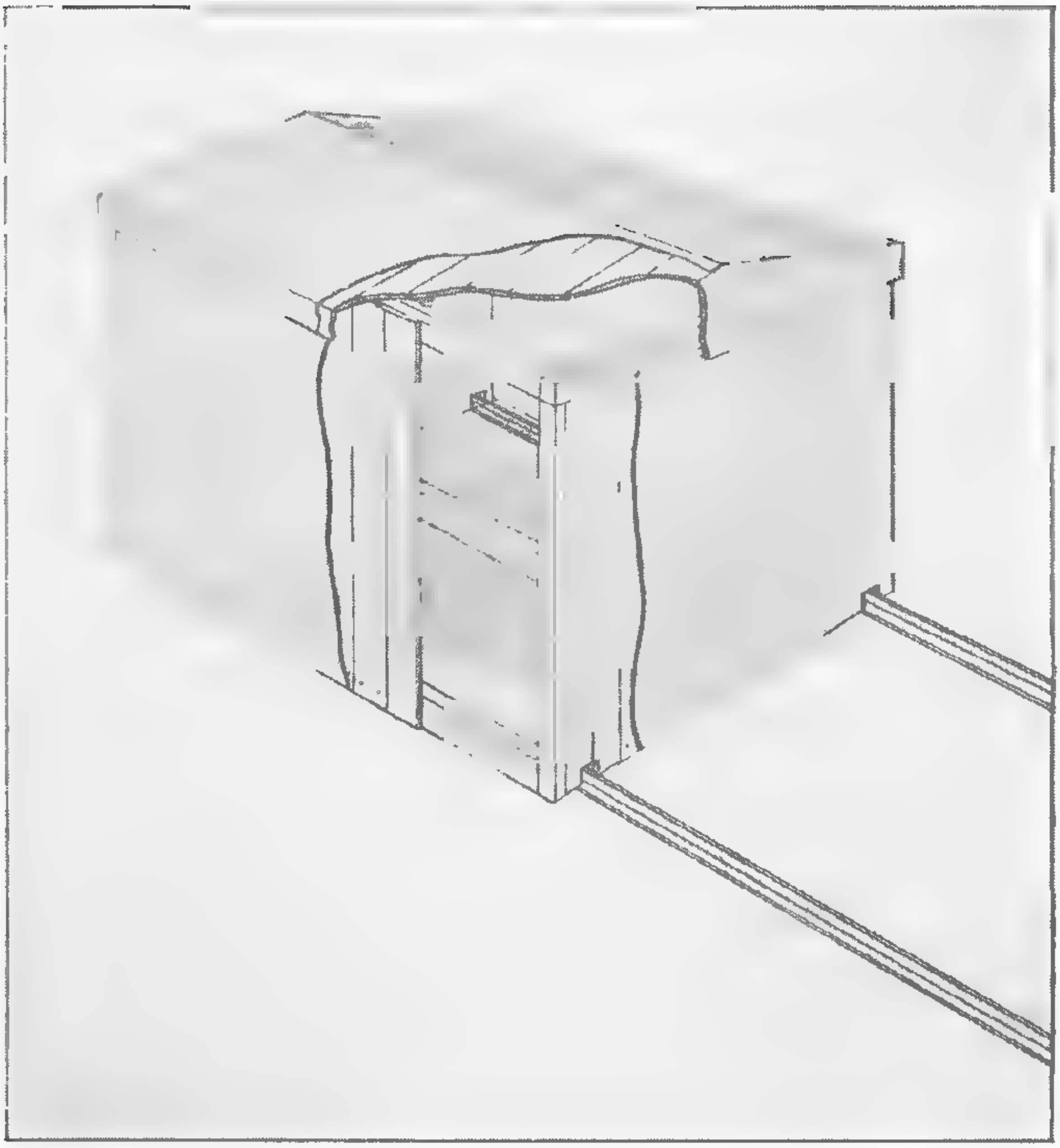


Fig. 46—Telescope housing

Slide-off type, constructed from 3" × 2" framing covered with ½" matching and roofing felt. Mounted on four wheels grooved to run on rails made from T iron

is generally beyond the means of the amateur, but there are several alternative methods of providing a housing for the telescope. The simplest is perhaps in the form of a small shed, just sufficiently large to cover the telescope, and which

is provided with wheels and a runway so that it can be rolled away from the telescope. A suggested construction is shown in fig. 46.

Fig. 47 shows another simple form of construction, where the roof is made to slide off in two sections, with a rain-proof

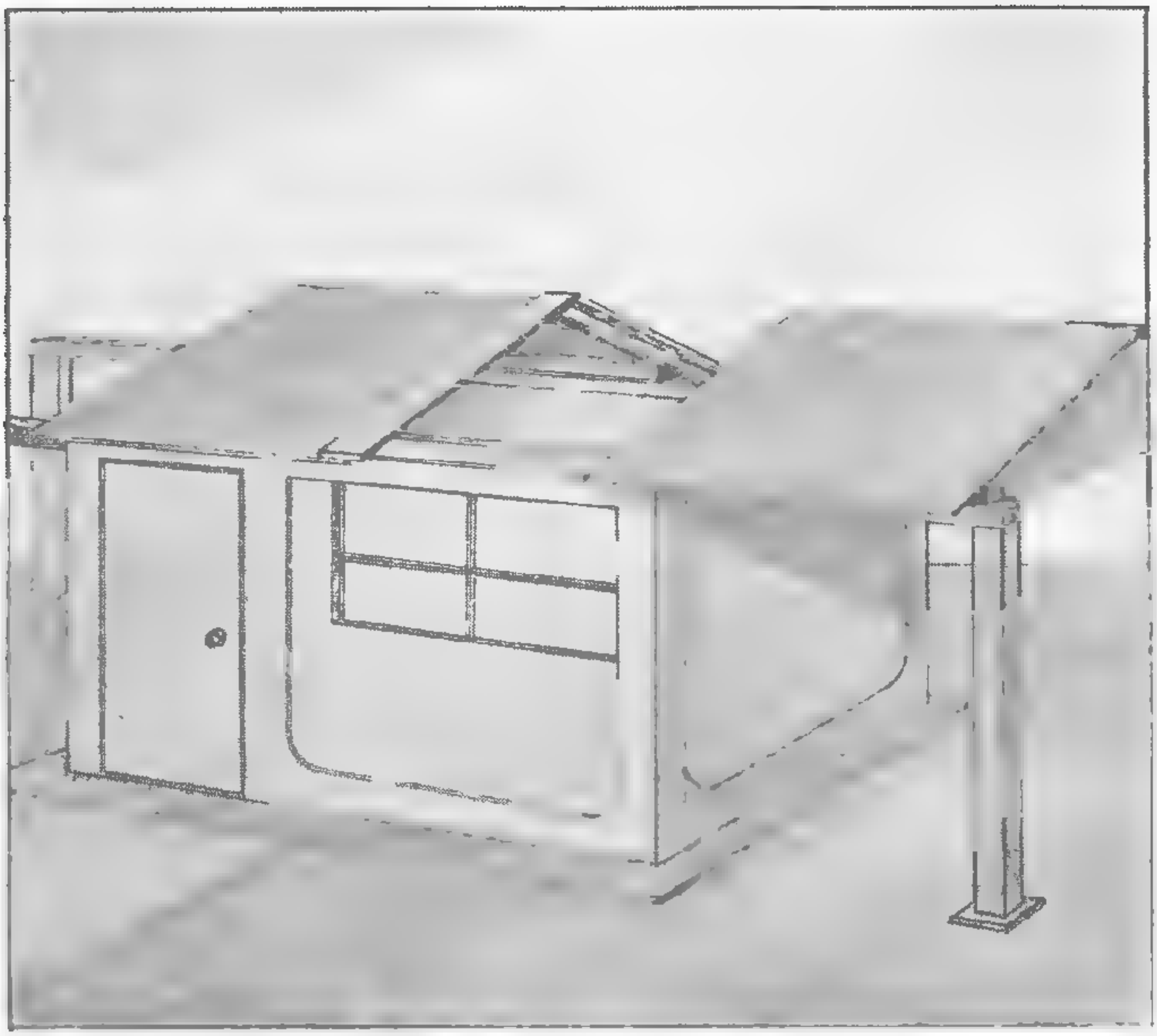


Fig. 47—Observatory

Slide-off roof in two sections. Timber construction covered with roofing felt. Concrete floor

centre joint. Other forms of construction are given in figs. 48 and 49, which may help the reader to decide upon the housing most suitable to his taste and means. Whatever type is decided upon, make sure that it is weather-proof. This is simple enough in an ordinary shed, but where the roof has to slide off, or a section made removable, particular care must be taken at the joints, and any gaps efficiently baffled so

that rain or snow will not be blown into the housing. As regards size, a permanent housing, as distinct from the slide-off cover, should not be less than 12 ft. square. The amount

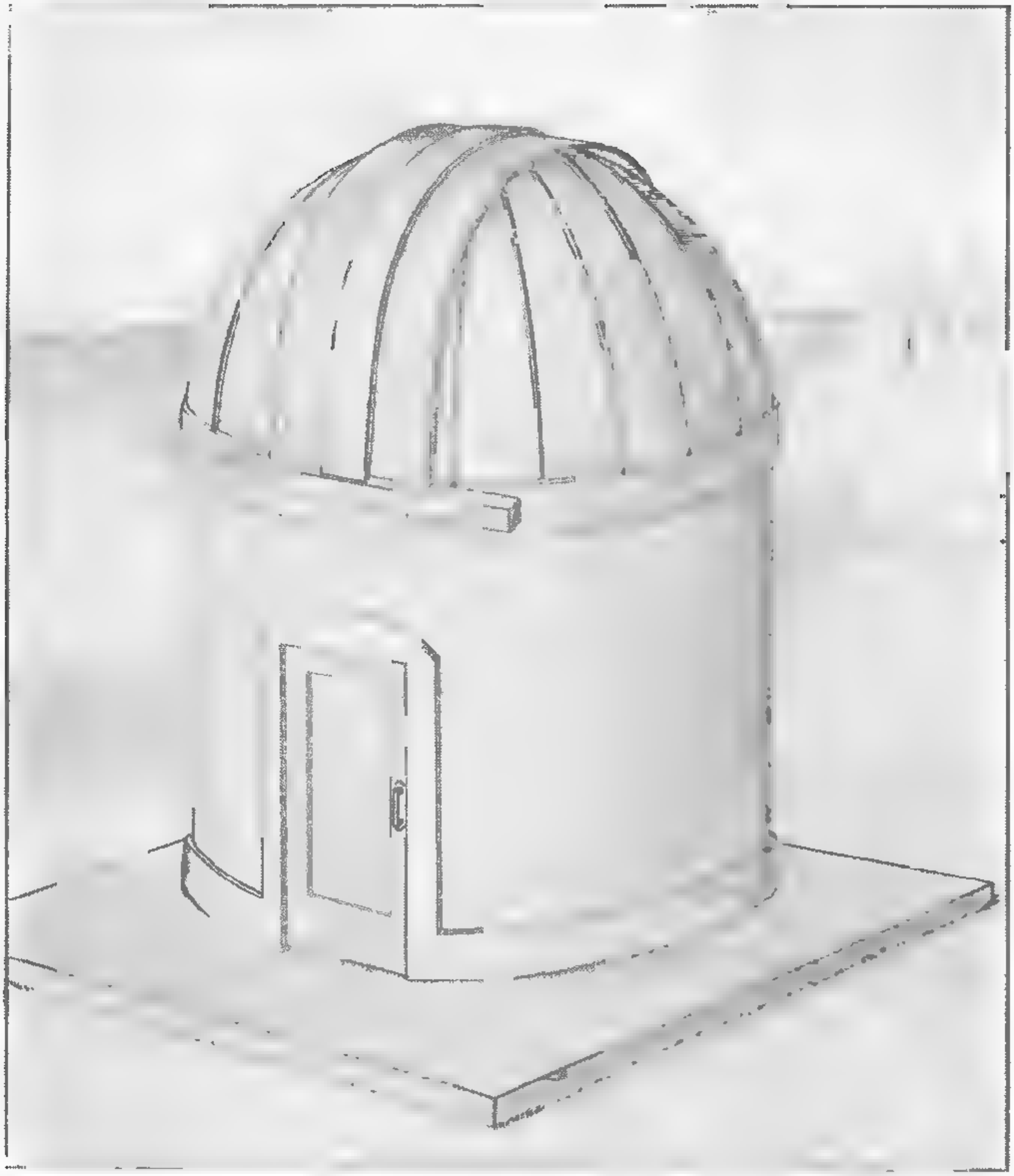


Fig. 48 —Observatory

Dome type, with opening covered by sliding hatch in two sections. Whole observatory including walls rotates on runway built into concrete floor

of material used will not be so very much more than one of smaller size, and the extra space will be appreciated when you come to use the telescope.

Fig. 50 shows how to cut out the segments to form a dome, and these can either be fixed to wooden or steel ribs forming a framework to the dome, or if made in sheet metal the edges

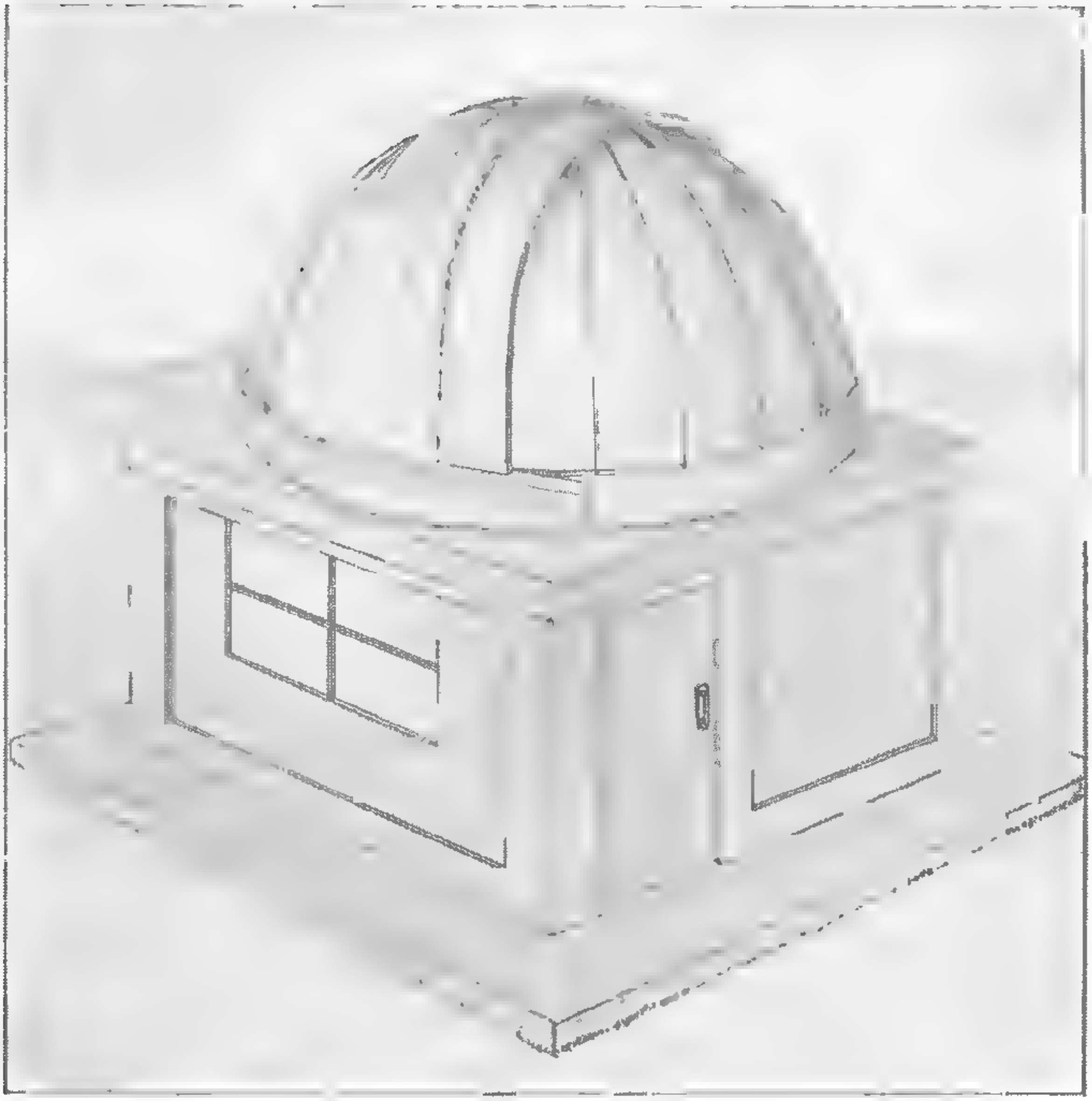
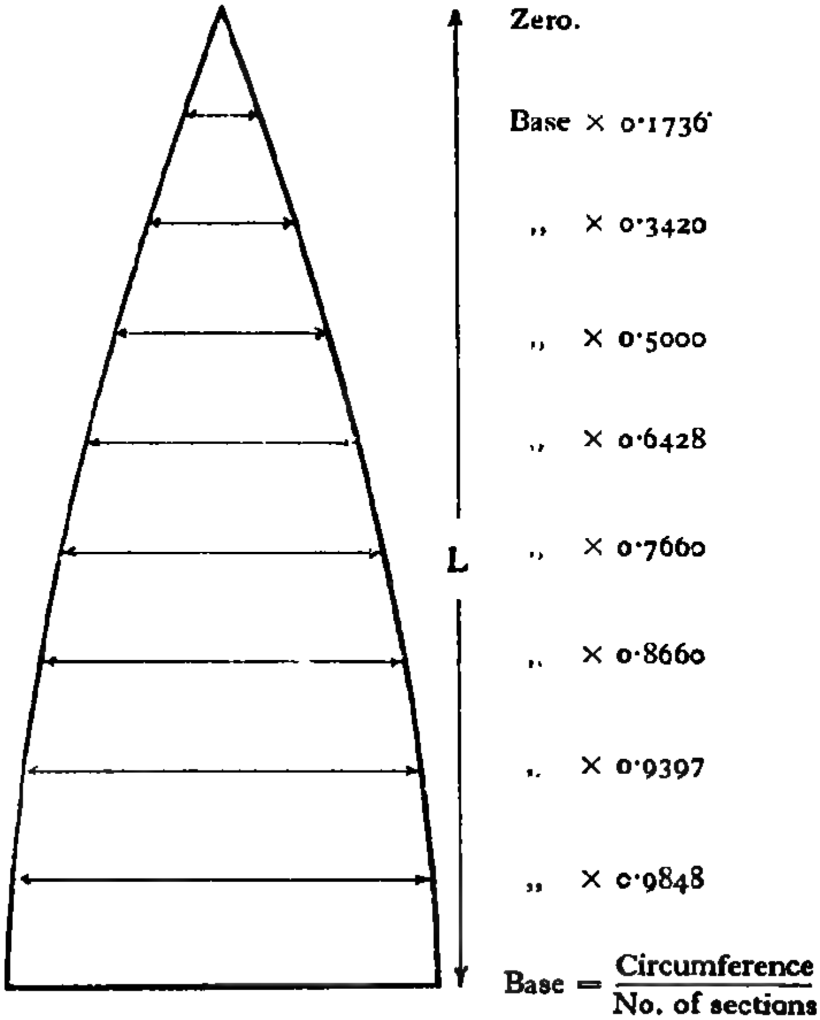


Fig. 49.—Observatory

Dome type, similar to fig. 39, with dome revolving on track built on to top of roof

of each segment can be joined together in the form of a " double-turned standing seam ", which will be self supporting.

The advantage of a permanent housing for the telescope will soon be found when you come to use the telescope in a high wind.



$$L = \frac{\text{Circumference of dome}}{4}$$

Fig. 50.—Method of marking out section of dome

Conclusion

The instructions given in this book for the construction of an astronomical telescope are not exhaustive, but they should prove sufficient to enable you to make an instrument which will give you many hours of pleasure both in construction and use. As in most subjects demanding some mechanical skill, experience is the only efficient teacher, and for that reason the basic principles only have been given, with one or two tips based on the writer's own experience.

I would once again like to warn you (or to assure you) that even if you set out with the object of making just one telescope of modest aperture, the probability is that you will end up by making a super instrument of perhaps 12 or even 18 in.

diameter, fitted with camera, spectroscope, filar micrometer, and a hundred and one other gadgets. That is certainly my aim when time and circumstances permit. So in designing your mounting and housing, bear this in mind.

You will no doubt find when you set out to make your telescope that your not so mechanically minded friends will ask, " What is the use of it?" This is a question which can be asked of dozens of other hobbies. Why do people collect stamps and birds' eggs? Why do others spend hundreds of man-hours collecting and making clocks, or constructing model railways? The whole object of a hobby is to spend your leisure time in doing something which interests you. In the case of telescope-making, the mechanic will find plenty to absorb his skill and interest, and those whose interest is astronomy will be in possession of an instrument which will enable them to probe deep into the universe. To those unacquainted with the subject, astronomy may appear a dry and uninteresting study, but to the amateur astronomer, gunning for comets or meteorites with a telescope and camera can be just as exciting as gunning for big game; and the discovery of a new star or some other body in the universe gives all the thrills experienced by the explorer.

Wherever your interest lies, let me wish you the best of luck in the construction of your first telescope.

CHAPTER XII

An Inexpensive Mounting

The following pages describe a mounting which I designed not as a perfect instrument, but as one which could be constructed at the minimum cost of materials and with the ordinary hand tools at my disposal, and yet would still embody the basic principles of construction and present a pleasing appearance. It also had to be portable and, although primarily intended for a 6-in. mirror, it could with very little modification be used for an 8-in. or 10-in.

Before proceeding with the actual construction in galvanized sheet iron, I made a scale model ($1\frac{1}{2}$ in. to the foot) from stiff drawing paper and glue, and would pass this on as being well worth while for any project in sheet metal. Not only does it give a three-dimensional view of the finished product, but certain constructional and operational difficulties will be made apparent, which might not be foreseen in the original design—and it is much cheaper to scrap a paper model than to have to remodel a sheet-metal one.

One feature of the construction was the minimum use of rivets. In place of these, the sheet metal was utilized by drilling a $\frac{3}{16}$-in. diameter hole in one of the faces to be joined, and punching the metal of the other face through the hole with a pointed taper punch, and then spreading the jagged edges of the punched metal to grip the first sheet, and hammering flat. As such a joint is weaker than a rivet, the holes were made at shorter intervals than would have been the case if rivets had been used. The final mounting as constructed had proved to be very satisfactory in use and I think has fulfilled all the requirements originally contemplated.

The Base

This is constructed entirely from wood, except for the supports for the two main bearings, which are held between $\frac{1}{16}$-in. flat steel plates screwed to the cross-bracings. As will be seen from the frontispiece, I have enclosed the base with sheet metal, but this was done purely from an æsthetic point

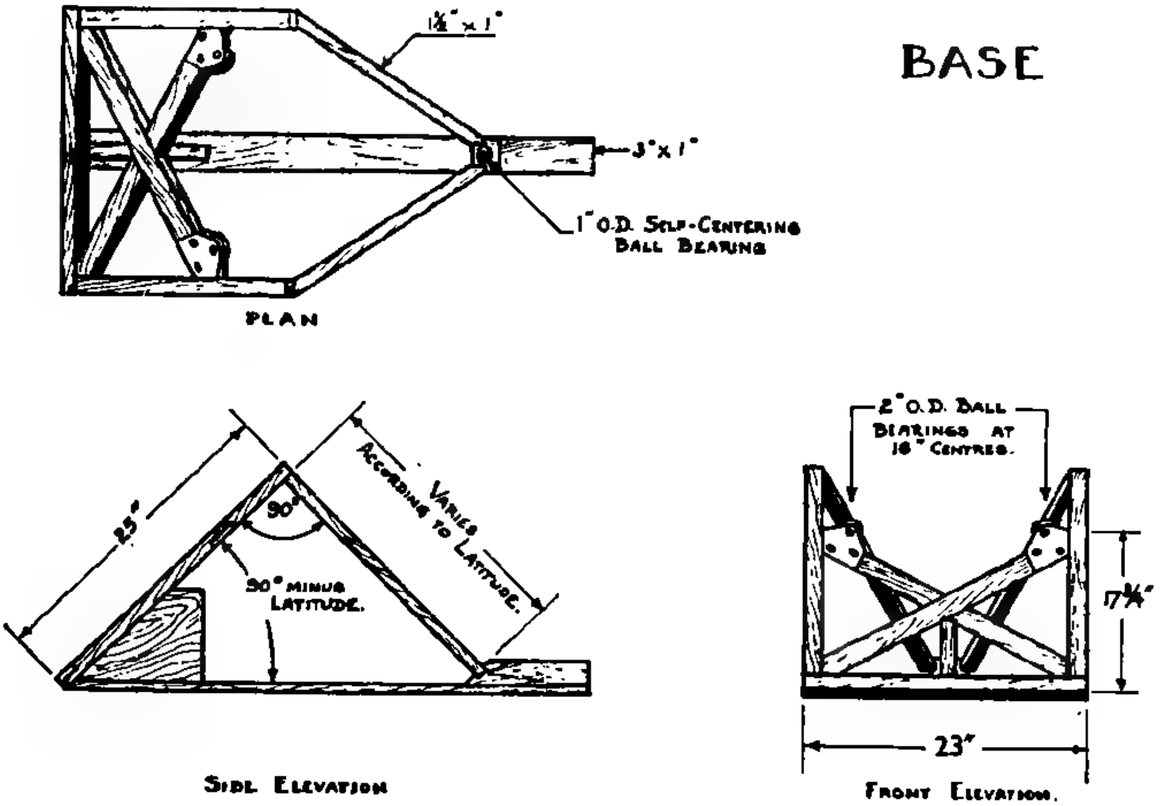


Fig. 51

of view and is not really necessary from the construction aspect as it does not add appreciably to the rigidity. I have not given details of the dimensions of this cladding as they would vary according to the angle of the polar axis, and in any case are simple geometric shapes which can best be dimensioned by measuring the finished wooden structure.

The Polar Axis

Basically this consists of two cones fixed at their bases to a wheel which forms the main bearing, and the upper cone carries a cylinder which holds the bearings for the declination axis. Additional rigidity is given to the cylinder by three

wooden disks placed at the centre and ends, the end ones carrying the ball bearings for the declination axis. The main bearing wheel on the polar axis is a built-up wooden disk, 18 in. diameter by 1½ in. thick, fitted with a metal rim, similar to a cart wheel. The rim is made from 1½-in. by $\frac{1}{32}$-in. strip steel, with the ends bent at right-angles for a distance of ½ in., which fit into a slot in the wooden wheel. A fly-wheel would

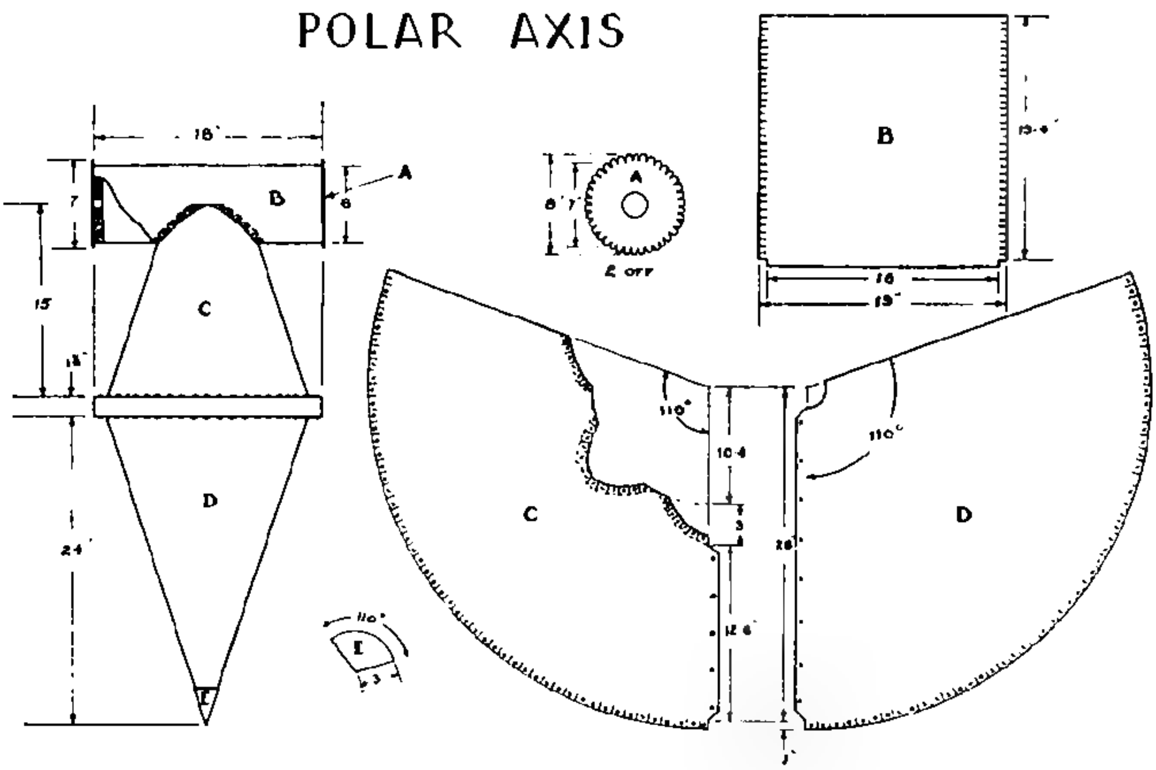


Fig. 52

have been preferable from the point of view of accuracy, but would have added considerably to the weight of the mounting and would also have necessitated a much stronger base. Provided the wheel is carefully made it will suffice for this particular mounting, which does not claim to be dead accurate, and will be found to give good service in operation. The bases of the cones are fixed to the wheel by means of ½-in. round-head brass screws. The cylinder is fixed to the upper cone by aluminium rivets, as the location of the holes on the flanged portion of the cone does not permit of the use of the method previously described. The ends of the cylinder are cut and turned up through 90° to form flanges, and the end

plates marked " A " are fixed by turning the tabbed rim over the flange. The small cone marked " E " is necessary because it is very difficult to form a point on a large cone without a special former. Incidentally the cones were bent to shape over a length of ½-in. diameter steel rod held rigidly in the vice and consist of a series of bends rather than a rolled effect.

The Tube

I think the drawing of the tube is more or less self-explanatory and follows the general scheme of tabbed joints using the sheet metal to form the rivets. An exception to this is the

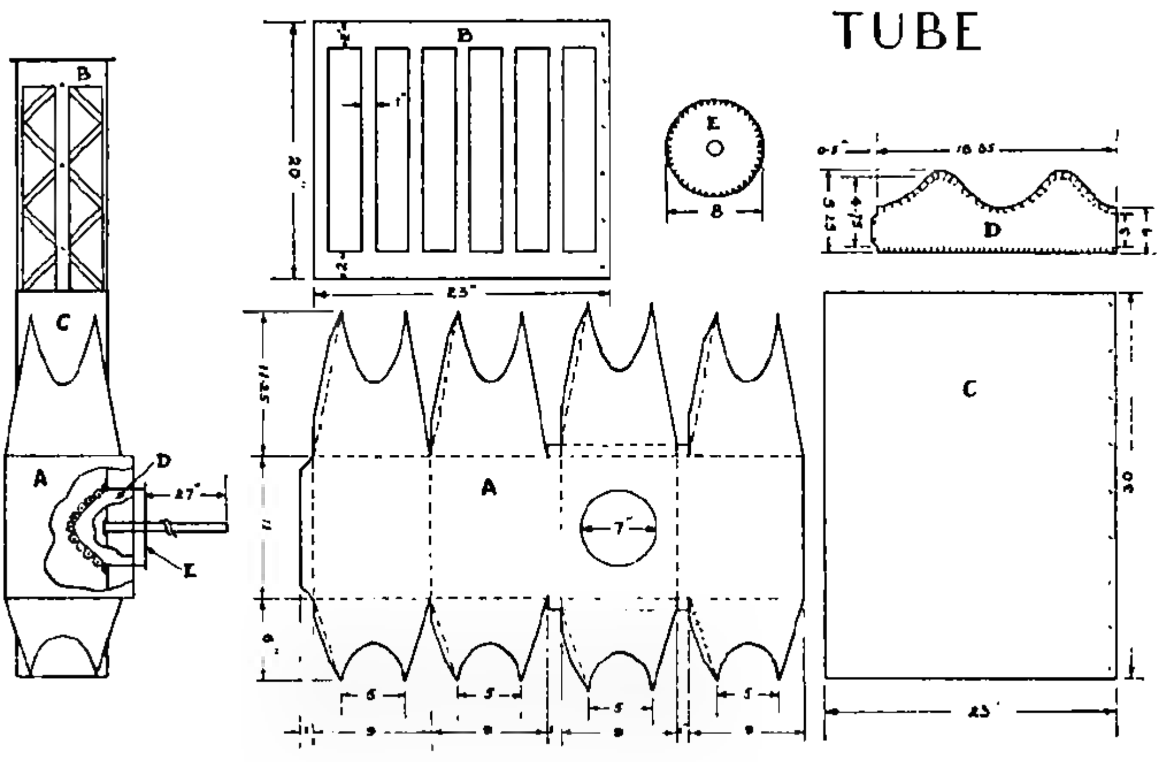


Fig. 53

parabolic curves formed where the square box section meets the cylinder of the tube. These joints are soldered. This also applies to the ½-in. wide ring at the top of the lattice tube which is soldered on to give rigidity. The prism holder is the same as described on p. 76, and the threaded ends pass through holes located at the top end of three of the longitudinal ribs. The eyepiece holder consists of a square piece of sheet metal with a centrally off-set ring to take a standard-size eye-

piece, located so that the eyepiece comes opposite any of the triangular openings formed by the diagonal bracing. By this means a comfortable observing position can be arranged by moving the eyepiece to any one of the six openings and rotating the prism accordingly.

The mirror end of the tube is fitted with three lugs designed to hold the mirror cell on the bayonet-type principle. The lugs and the projections on the mirror cell should be marked or numbered so that the mirror can be readily located in the one position.

The Mirror Cell

This also is made from galvanized sheet iron and is essentially a flat round cell of 7 in. diameter, with a $\frac{1}{2}$-in. flange around the upper rim. Three round-head or cheese-head

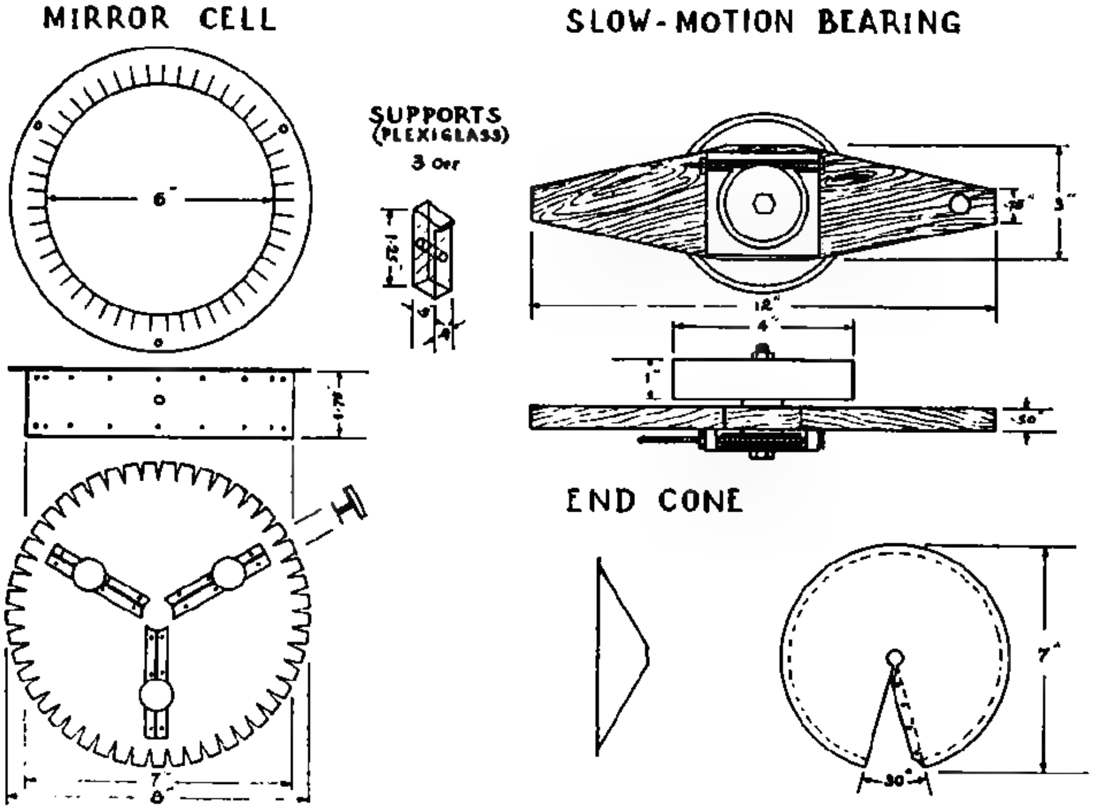


Fig. 54

screws are soldered to this flange with sufficient clearance between the heads and the flange to allow them to engage in the slotted lugs on the telescope tube. Three T-shaped ribs fixed to the bottom of the cell provide reinforcement to the

bottom, and carry three circular disks covered with leather pads on which the mirror rests. Supports at the side and top of the mirror are made from $\frac{3}{8}$-in. thick Plexiglass formed as shown; they are fixed by means of brass screws to the rim of the cell. The holes in the rim of the cell should be slightly oversize or slotted to permit adjustment of the Plexiglass supports.

The Counter-balance

This consists of two cones fastened together at their outer edges, with a sheet-metal sleeve bearing passing through the centre so that it can slide over the $\frac{5}{8}$-in. diameter tube which forms the central part of the declination axis. Between the

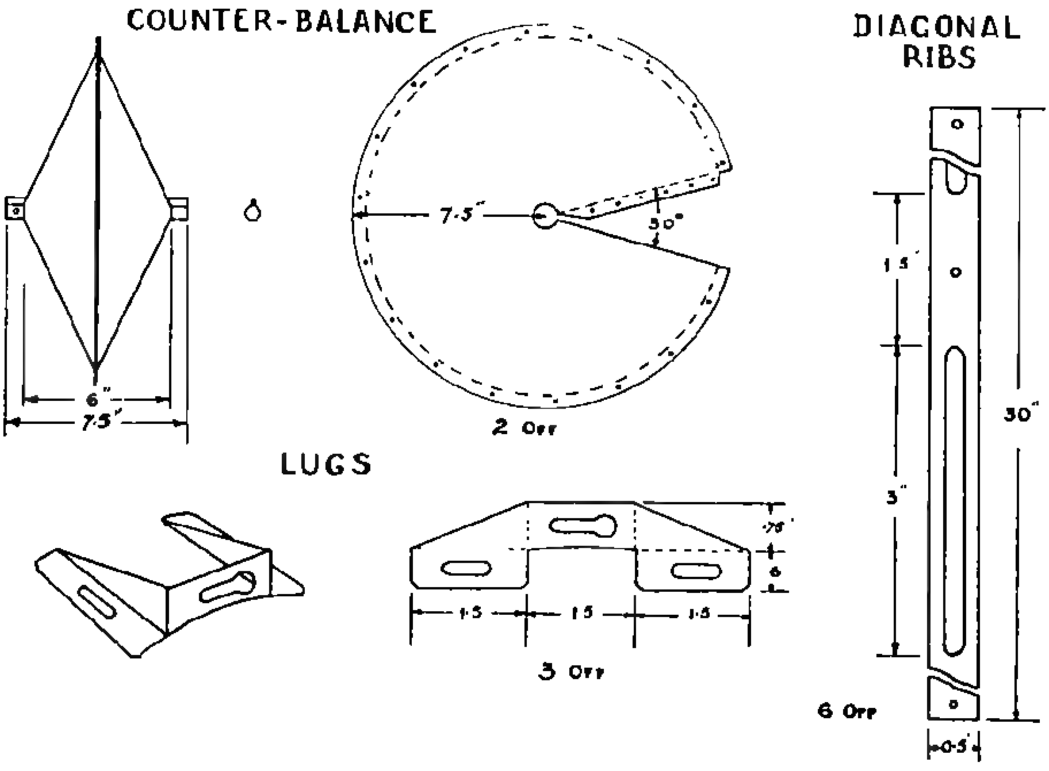


Fig. 55

counter-balance and the declination-axis cylinder is another " end-cone " which is held tight against the face of the cylinder by means of a hose-type clamp on the central tube. In constructing the counter-balance, an opening is left in the joint at the rim, and when the telescope is assembled, concrete is poured into this opening so that the weight of the tube is counter-balanced and the polar axis rotates easily on its two

main bearings. The jointing at the rim is then completed. A hole is drilled through the sleeve on the counter-balance and the central tube to take a taper or split pin which will prevent movement of the counter-balance along the tube. A taper pin is to be preferred if the mounting has to be assembled and dismantled every time it is used.

The Slow-motion Bearing

In addition to its main function of rotating the polar axis slowly, this also serves as a friction brake on the polar axis. It consists of a 4-in. diameter rubber-faced truck wheel capable of being rotated by a worm-and-wheel drive. The whole is mounted on a rigid support pivoted at one end and located on the base so that the rubber-faced wheel can be brought into contact with the rim of the main bearing wheel and held there by a spring action.

The worm and wheel I used was not originally intended as such. It consists of a flexible steel cable which passes over a grooved wheel, and I believe it came originally from some aeroplane part. By suitable modification this was made to form the worm and wheel, by utilizing the cable as the worm which engaged in the grooved wheel. A piece of brass rod about 2 ft. long was fitted to the free end of the cable, and a small circular handle attached to the other end of the brass rod. By this means, the handle could be held in the hand whatever the position of the telescope tube, and the slow-motion mechanism operated.

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